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AULT FEATURES IN SOILS OF THE MEHRTEN FORMATION, AUBURN DAMSITE, CALIFORNIA

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SPECIAL REPORT 141

FAULT FEATURES IN SOILS OF THE MEHRTEN FORMATION, AUBURN DAMSITE, CALIFORNIA

By

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ABSTRACT

Fault features involving soil and clay formation were used to establish probable age relationships concerning recency of displacement along the Maidu East fault zone near the proposed Auburn dam. Major displacement along the Maidu East fault zone occurred after the beginning of the Pleistocene and before pseudopaleosol development during the late Pleistocene. Despite some striking initial appearances, no unequivocal evidence for more recent movements along the fault zone was found. Detailed analyses (pH, particle size distribution, Ca/Fe ratios, and clay mineralogy) of three soil profiles on either side and above the main fault break in BHT–53 showed no clear offset. We found no conclusive evidence for tectonically generated slickensides within the pseudopaleosol, even though tectonic slickensides occur in relatively unweathered portions of the fault zone. Nevertheless, there is a slight chance that small displacements along the Maidu East fault zone could have occurred during the late Pleistocene without being recorded in the strata available.

There are two basic types of soil and clay formation within these features. The first, under good drainage, produces reddish clays in which only halloysite and iron oxides dominate. The second, under poor drainage, produces grayish clays in which both halloysite and montmorillonite dominate and iron compounds are reduced.

A probable sequence of events concerning the age of the Maidu East fault includes the following:

(1) Deposition of the Mehrten Formation in a river channel during the Miocene about nine million years ago.

(2) Downcutting of the American River through Mesozoic bedrock during the Pleistocene beginning about two million years ago with accompanying soil formation on the now–abandoned river channel.

(3) Displacement and fracturing of the Mehrten Formation along the Maidu East fault zone.

(4) Formation and translocation of halloysitic clay and iron oxides within the relatively well–drained shears of the fault.

(5) Erosion and 30–meter recession of the fault scarp west of the main shear in trench BHT–53.

(6) Eventual plugging of shears within the fault zone leading to decreased permeability and perched water conditions.

(7) Montmorillonite and continued halloysite formation under reducing conditions within shears and fractures resulting in "pseudopaleosols." These occur beneath the normally oxidized zone of well–drained soils. They are irregular clayey bodies that may be mistaken for paleosols though they do not directly represent formerly stable land–surfaces. Pseudopaleosols are forming contemporaneously though their principal development appears to have occurred prior to the Holocene.

(8) Extensive slope stripping and deposition of the Foothills colluvium during the early Holocene pluvial period.

(9) Partial re–oxidation of upper surfaces of pseudopaleosols either as a result of local slope stripping without subsequent deposition (BHT–106) or as a result of reduced precipitation during the Holocene (BHT–53).

FAULT FEATURES IN SOILS OF THE MEHRTEN FORMATION, AUBURN DAMSITE, CALIFORNIA*

By
Glenn Borchardt[1], Gary Taylor[2], and Salem Rice[3]

INTRODUCTION

Backgrouond and Purpose

Concerns for the seismic safety of the proposed Auburn dam were greatly stimulated by the Oroville earthquake of August 1, 1975 (Carter, 1977, p. 646). Although it was a relatively small earthquake (5.7 magnitude), it acquired considerable significance because it was accompanied by surface rupture along a previously unknown fault in the Foothills fault system. The latter is a system of many faults that trends northwest through an area about 200 miles long and up to 30 miles wide in the western foothills of the Sierra Nevada (Clark, 1960). The Auburn damsite, in the canyon of the American River near Auburn, lies within this zone of faulting.

Prior to the Oroville earthquake all of the faults in the Sierra foothills region were assumed to have been inactive for many tens of millions of years (Clark, 1960, p. 494), and seismic design criteria for the proposed high, thin arch dam near Auburn were established under the assumption that there were no local active faults. Following the Oroville earthquake, however, wide-ranging studies were initiated by the U.S. Bureau of Reclamation to determine whether or not parts or all of the Foothills fault system, particularly the faults in the damsite area, should be considered active. The Bureau proposed that a thin arch dam should not be constructed at the site if faults traversing the dam foundations are active (see Carter, 1977, p. 649).

The dam foundations are in Paleozoic and Mesozoic metamorphic rocks traversed by numerous faults and shear zones (Lindgren, 1894; Gardner and others, 1957). Erosional remnants of the much younger Mio–Pliocene Mehrten Formation (about 9 million years old, O'Brient, 1978, p. 11) occur on the uplands on the west side of the canyon. These sedimentary rocks, consisting of volcanic conglomerates, tuffaceous sandstones, and lahars (volcanic mud flows), have been eroded extensively since Pliocene time (Shlemon, 1972), as the American River canyon has been etched deeply into ancient bedrock.

One of the products of the post–Oroville earthquake studies undertaken by the Bureau was the discovery of the Maidu East fault zone (Figure 1) cutting the Mehrten Formation near the damsite, the first direct evidence found for post–Mesozoic faulting in the area. Mehrten beds are displaced by as much as 5.5 meters (vertical component) about 800 meters from the right abutment of the dam. This discovery resulted in extensive trenching and related studies of the Maidu East fault to determine whether or not the fault zone is still active.

The criterion used by the Bureau of Reclamation to define an active fault is displacement on it within the last 100,000 years. Determination of the age of fault displacements generally requires the recognition of offsets of geologic materials of known age. In the Auburn area, the only stratigraphic units even approaching such a relatively youthful age are soils and paleosols (fossil soils).

The stratigraphy and chronology of the paleosol remnants overlying the Foothills fault system were evaluated in a companion paper (Borchardt, Rice, and Taylor, 1980). In brief, that report supports the hypothesis that "the 'Foothills paleosol' was an active soil between 9,000 and 130,000 B.P. (years before present)." Field observations and laboratory data presented in that paper indicate that the foothills of the Sierra Nevada were relatively stable during the Wisconsin age glaciation, but that extensive slope stripping occurred during the early Holocene pluvial period about 9,000 B.P. This slope stripping produced the "Foothills colluvium" of the same age which now overlies remnants of the paleosol along the Foothills fault system north and south of Auburn. At a few sites, slickensides coincident with tectonic shears in the bedrock extend through the paleosol. Their preservation within soil layers normally subject to shrinking and swelling that would destroy them indicates that fault movement occurred along the system since the paleosol ceased being an active soil.

Unfortunately, these superficial materials were stripped from the faults in the dam foundation by construction prior to the recognition of possible active faulting in the Sierra foothills. However, they are still present over much of the Maidu East fault zone to the south of the right abutment.

The objective of this study was to evaluate the features and factors that involve soil formation along the Maidu East fault zone as it traverses the Mehrten Formation, and to apply these evaluations to determine the age of the most recent fault displacements there.

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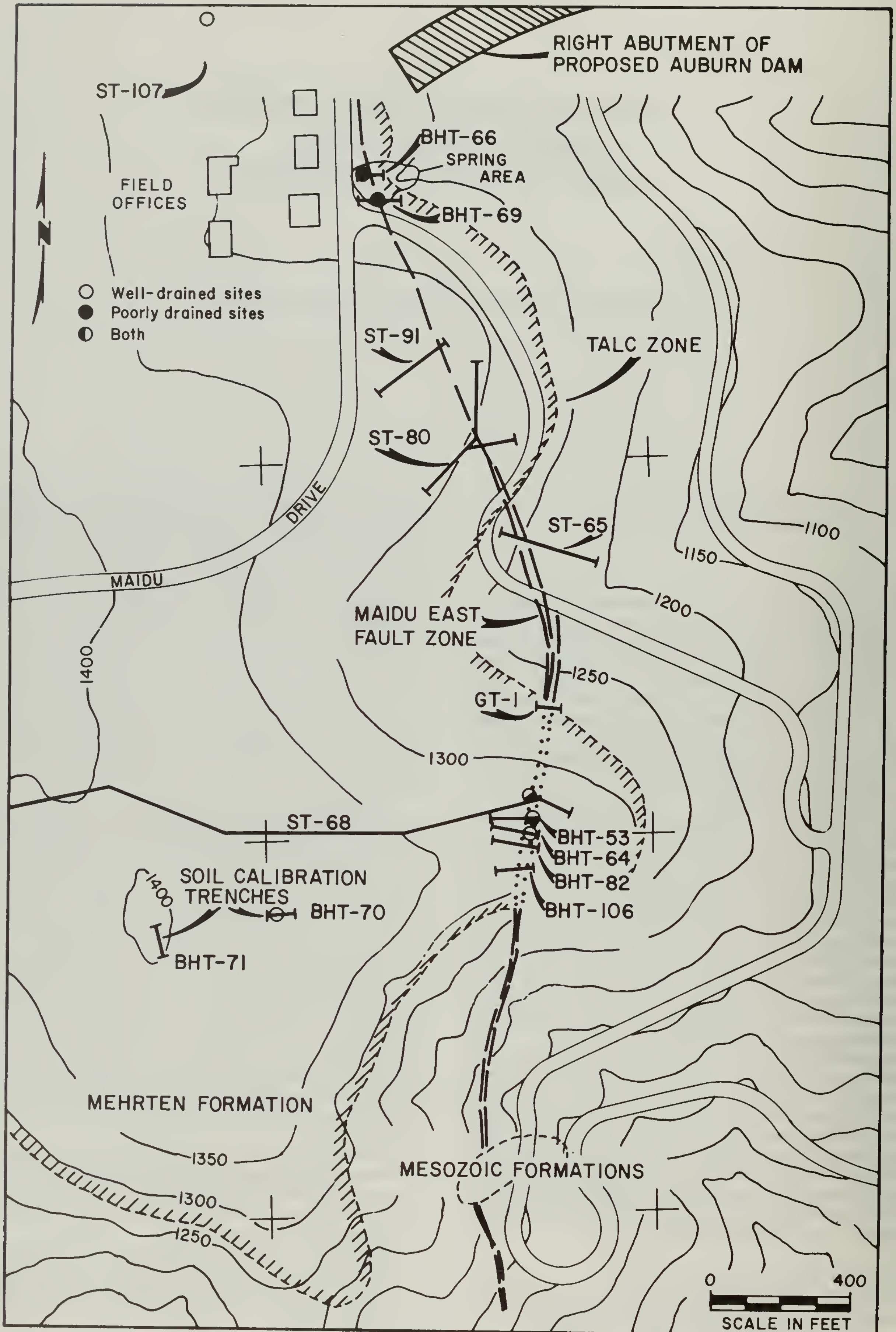

Figure 1. Sample locations along the Maidu East fault zone as it cuts the Mehrten Formation near the right abutment of the proposed Auburn dam (modified from Shlemon, 1977b).

Methodology

The techniques available for evaluating fault features in soils encompass a wide range of field observations and laboratory analyses. Almost any determination helps to characterize a soil and thereby limits the range of genetic interpretations that can be placed upon it. Studies of recency of faulting in soils are just beginning. Accordingly, the tests most valuable for this endeavor will gain prominance as this new discipline evolves. As in any science, we compare samples for differences and for similarities. From these data (Tables 1 and 2), we attempt to deduce the relative ages and tectonic history of soils, paleosols, and other pedogenic features. Laboratory methods chosen for this particular study were, for the most part, standard techniques of soil science (Appendix). Field sampling was in response to the varying conditions of each site. No set pattern was maintained except to obtain representative samples whose analyses were likely to answer questions prompted by field observations and the available literature.

Acknowledgments

We wish to thank the following laboratory personnel who analyzed the samples: Hasu Majmundar, Manager; Marc Loza, Bill Wong, Connie Celum, Charles Smith, and Lydia Lofgren, Laboratory Technicians. We thank Richard Kilbourne, who identified the pollen grains and helped sample some of the soils. We greatly appreciate the advice and encouragement given by Richard Stewart, Forrest Bacon, and Tom Gay. We also wish to thank Delores Patterson and Marianne K. Roja for typing the manuscript.

We would especially like to thank those personnel of the U.S. Bureau of Reclamation, Woodward–Clyde Consultants, the California Department of Water Resources, and the U.S. Geological Survey for their help in providing trenches and access to sites as well as for their many helpful discussions concerning the soils and the geology.

SOIL FORMATION

This is the first of the four sections making up the body of this report. In this section we evaluate clay mineral formation in soils developed on the andesitic Mehrten Formation as a result of varying drainage conditions. In the section entitled "COLLUVIUM" we call attention to certain geomorphic details such as the pronouonced stoneline at the base of the Foothills colluvium, the fault–line scarp, and the lithologic change in the supposed "colluvium" overlying the Maidu East fault zone. In the next section, "GENESIS OF CLAY WITHIN FAULT FRACTURES," we test the contradictory hypotheses of Shlemon (1977a) and O'-Brient (1978) concerning the origin of the brown clay within fractures of the fault zone. In the final section, "SOIL DEVELOPMENT AND TECTONISM AT TRENCH BHT–53," we consider the above information along with additional laboratory data in a detailed study of a soil tongue or "pseudopaleosol" developed within the fault zone, and derive a probable sequence of events concerning the age of the Maidu East fault zone.

Essentially two contrasting environments of soil development occur in the Mehrten Formation near the proposed Auburn dam. The first involves good drainage and leaching of elements such as calcium, magnesium, and silicon, oxidation and accumulation of transition elements such as iron, and a reduction in pH by humic and carbonic acids. The second involves poor drainage and an accumulation of elements including magnesium and silicon as well as iron in its reduced state. The well–drained areas are by far the most extensive in the Mehrten Formation.

Well–drained Soils

There are three slightly different types of soils developed in well–drained positions in the Mehrten Formation. The nearly level drainage divide at trench BHT–70 is the most typical landscape for soils of the Mehrten conglomerate. The soil at trench ST–68, on the remnant of a fault–line scarp consisting of Mehrten sandstone overlain by about a meter of locally derived colluvium, is a special case exemplifying deep oxidative weathering. The soil at trench ST–107 is a highly weathered deposit consisting of older Mehrten–derived colluvium.

SOIL ON CONGLOMERATE

Trench BHT–70 was dug to expose soils on a relatively stable drainage divide on the Mehrten Formation (see soil description in Shlemon, 1977a, p. 35). According to Shlemon (1977a, p. 33), this soil, like other well–drained soils on the Mehrten conglomerate, is an Ultic Argixeroll. An Ultic Argixeroll is an acidic soil (Ultic) that contains at least 20 percent more clay in the B horizon than in the A horizon (argi), forms under a Mediterranean climate (xer), and has a dark–colored, thick, humus–rich A horizon (oll) (Soil Survey Staff, 1975, p. 311). The laboratory data (Table 2) support this classification, except that the sample from the B2t horizon had only 12 percent more clay than the Al horizon. However, the difference in clay content between the A and B horizons was shown to be highly variable when a more detailed sampling in nearby trench BHT–53 (Figures 1 and 2) exhibited differences ranging between –9 and 94 percent.

The soils in trench BHT–70 are noticeably redder (Williams and Yaalon, 1977) than those in BHT–53. For example, the B2 horizon in BHT–70 is yellowish red or dark reddish brown (5YR5/6d, 3/4m) while in BHT–53 it is brown or dark yellowish brown (10YR5/3d, 3/6m). Apparently, the darker colors of BHT–53 result from a greater accumulation of organic matter at this more heavily forested site. Also, the soils near BHT–53 have undergone considerably more erosion during the last colluvial episode. These soils therefore contain a greater proportion of less weathered parent material. For example, the soil on the ridge just south of BHT–53 (trench BHT–106) exhibits very little B–horizon development, being nearly an AC profile; the thin, dark soil here overlies a section of conglomerate that is very light in color, which indicates that it has undergone less supergene weathering than most other Mehrten surfaces.

A particularly important aspect of soil formation and age dating involves the thickness of the colluvial unit within these soils. Often, it has been assumed that the depth of colluviation on the Mehrten Formation and the soil–parent material boundary were one and the same (Shlemon, 1977a p. 13; Frei and others, 1977, Drawings no. 7350 and 7351). In general, this is not the case. It is, of course, difficult to evaluate the depth of colluviation in soils of such cobbly nature. However, careful examination of the upper portions of soils on conglomeratic parent material reveals what, for lack of a better term, we call "angular orphans." Angular orphans are "angular fragments separated from weathered, well–rounded cobbles in colluvium derived from conglomerate." Angular orphans result from soil

Table 1. Particle size distribution, pH, and qualitative clay mineralogy of the well–drained soil in trench ST–68 and the poorly–drained soils elsewhere in the Mehrten Formation.

				PARTICLE SIZE DISTRIBUTION															Clay Mineralogy Peak/Background			
				Total			Sand					Silt										
CDMG No.	Field No.	Interval sampled, cm	Horizon	Sand	Silt	Clay	Very Coarse	Coarse	Medium	Fine	Very Fine	Coarse	Medium	Fine	Gravel	Texture	pH	cos[1]/fs	Hl	Mt	s/si	msi/fsi
				2-0.05	0.05-0.002	< 0.002	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	>2 mm[2]				7.2A	17A		
				Percent of <2mm													paste method					
									Soil Profile in Trench ST-68													
313/77	77B152	0-15	A1	30.0	50.2	19.8	2.8	3.6	7.1	9.7	6.8	12.0	23.4	14.8	6.2	sil	5.48	0.37	0.72		0.60	1.58
314/77	77B153	15-45	B1	28.5	47.0	24.5	2.0	2.2	5.0	9.8	9.5	11.5	20.5	15.0	1.1	sil	6.05	0.22	0.78		0.61	1.37
315/77	77B154	45-65	B2	27.0	45.0	28.0	1.6	2.2	5.2	10.2	7.8	12.7	18.9	13.4	0.0	cl	5.39	0.22	0.93		0.60	1.41
316/77	77B155	65-100	IIB2b	24.0	43.7	32.3	1.2	2.0	4.8	10.0	6.0	11.8	17.4	14.5	1.0	cl	5.33	0.20	0.93		0.55	1.20
317/77	77B156	100-135	IIIB2b	23.0	48.0	29.0	1.0	1.6	4.4	8.5	7.5	15.0	19.5	13.5	0.6	sicl	5.32	0.19	0.94		0.48	1.44
318/77	77B157	135-190	IIIB3b	28.6	37.0	34.4	1.4	4.1	6.9	9.4	6.8	11.4	14.6	11.0	0.8	cl	5.34	0.44	0.90		0.77	1.33
319/77	77B158	190+	IIIC	57.2	33.1	9.7	15.0	14.4	10.0	12.0	5.8	10.0	15.1	8.0	2.0	s1	6.03	1.20	0.79		1.73	1.89
									Soil Profile in Trench BHT-66													
294/77	77B122	0-56	A1	24.8	51.2	24.0	3.2	3.2	6.6	5.8	6.0	11.7	22.3	17.2	5.2	sil	5.92	0.55	0.57		0.48	1.30
295/77	77B123	56-76	IIB1bg	29.5	40.9	29.6	3.0	3.0	7.0	9.5	7.0	11.9	19.0	10.0	7.1	cl	5.98	0.32	0.72	0.37	0.72	1.90
293/77	77B121	76-110	IIB2bg	36.0	33.0	31.0	3.3	3.9	8.4	11.4	9.0	13.6	11.4	8.0	15.5	cl	5.92	0.34	0.89	0.52	1.09	1.43
292/77	77B120	110-170	IIIB2bg	24.0	27.4	48.6	0.8	2.4	7.8	9.7	3.3	4.0	14.0	9.4	0.0	c	5.81	0.25	1.07	0.74	0.88	1.49
									Sample from Trench BHT-69													
326/77	77B144	180-240	IIIB2bg	32.0	31.0	37.0	2.3	1.7	11.0	12.2	4.8	9.6	12.6	8.8	0.0	cl	6.19	0.14	1.39	0.64	1.03	1.43
									Sample from Fracture in Lahar (Mehrten Fm) at Sierra College Blvd.													
306/77	77B150	500-510	IIB2bg	5.0	10.2	84.8	0.4	0.3	1.3	1.8	1.2	4.0	4.4	1.8	1.2	c	5.92	0.17	1.01	0.48	0.49	2.44
									Sample from "pseudopaleosol" in ST-68													
270/77	77B011	360-370	IIIB2g	15.2	26.8	58.8	3.2	2.8	4.0	4.0	1.2	3.8	11.2	11.8	4.1	c	4.78	0.7	0.94	0.19	0.57	0.34

[1] cos/fs = Coarse sand content divided by fine sand content, Hl = Halloysite, Mt = montmorillonite, Peak to background ratios are maximum height of indicated peak minus the background divided by the background (these values must be considered only qualitative). The Hl peak at 7.2A was measured in the Mg saturated sample x-rayed at 54% relative humidity whereas the Mt peak at 17A was measured on the magnesium saturated ethylene glycol solvated sample.

[2] As a percent of the whole air dried sample.

Table 2. *Particle size distribution, pH, and clay mineralogy of well–drained soils and oxidized portions of the Maidu East fault zone in the Mehrten Formation.*

				PARTICLE SIZE DISTRIBUTION															Clay XRD Peak/Background				
				Total			Sand					Silt			Gravel								
CDMG No.	Field No.	Interval sampled, No.	Horizon	*Sand*	*Silt*	*Clay*	*Very Coarse*	*Coarse*	*Medium*	*Fine*	*Very Fine*	*Coarse*	*Medium*	*Fine*	*% of whole sample*	*Texture*	*pH*	*cos/fs*[1]	*Hl*	*Mi*	*Mt*	*Vr*	*Bd*
				2-0.05	0.05-0.002	0.002	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	2mm		paste method		7.2 A	10A	17A	14A	s/si
				Percent of <2mm																			
									Soil Profile in Trench BHT-70														
311/77	77B089	8-12	A1	31.6	47.1	21.3	2.5	3.5	6.0	11.2	8.4	16.4	18.6	12.1	4.7	sil	4.75	0.31	0.46				0.67
310/77	77B079	70-76	B2t	42.0	34.2	23.8	7.8	8.0	7.8	10.4	8.0	14.0	11.0	9.2	18.1	l	5.33	0.77	0.66				1.23
312/77	77B093	102-107	B3	43.2	34.0	22.8	6.6	7.0	9.4	12.0	8.2	13.0	13.0	8.0	8.6	l	4.63	0.58	0.79				1.27
									Soil Profile A in Trench BHT-53														
250/77	77B059	15-20	A1	33.5	47.7	18.8	3.5	4.5	7.0	10.5	8.0	15.5	19.0	13.2	28.2	sil	5.31	0.33	0.47				0.70
245/77	77B054	45-51	B2t	32.5	42.5	25.0	3.0	3.8	6.2	11.8	7.7	11.5	18.0	13.0	21.4	l	5.45	0.32	0.50				0.76
237/77	77B046	112-120	B3	45.2	32.7	22.1	8.8	8.7	10.5	11.0	6.2	10.7	13.1	8.9	5.1	l	5.57	0.79	0.54				1.38
236/77	77B045	130-136	R1	73.4	17.6	9.0	24.8	22.2	12.0	10.2	4.2	4.8	8.8	4.0	5.4	sl	6.26	2.18	0.46				4.17
									Soil Profile in Trench ST-107														
331/77	77B169	0-25	A1	26.0	60.1	13.9	3.5	3.0	4.9	7.6	7.0	18.0	36.0	6.1	6.0	sil	5.75	0.39	0.55	0.40	0.12		
330/77	77B168	25-60	B2	24.0	58.5	17.5	2.0	2.5	4.5	7.5	7.5	19.8	27.2	11.5	0.0	sil	5.48	0.33	0.54	0.14	0.14	0.21	0.41
329/77	77B167	135-145	IIB2b	32.0	39.6	28.4	1.8	3.2	7.6	11.0	8.4	15.0	15.5	9.1	0.0	cl	5.73	0.29	0.51			0.18	0.81
									Pink Matrix from Trench BHT-64														
291/77	77B117	85-95	R	75.6	12.7	11.7	15.0	16.6	29.6	12.8	1.6	2.6	6.8	3.3	8.7	sl	6.10	1.30	0.68		0.20		5.95
									Brown Clay from Trench BHT-64														
324/77	77B118	330-350	R	22.0	37.2	40.8	4.0	4.2	4.6	5.2	4.0	10.6	12.6	14.0	1.0	c	7.09	0.81	0.70		0.08		0.59

[1] cos/fs = Coarse sand content divided by fine sand content, Hl=halloysite, Mi=mica, Mt=montmorillonite, Vr =vermiculite, Bd=beidellite, Peak to backgrouond ratios are maximum height of indicated peak minus the background divided by the background (these values must be considered only qualitative). The H1 peak at 7.2A and the Mi peak at 10A were measured on the mg saturated sample x-rayed at 54% relative humidity whereas the Mt peak at 17A and the Vr peak at 14A were measured on the magnesium saturated sample solvated with ethylene glycol. The Bd peak at 14A was measured on the glycerol solvated sample in absence of Bd.

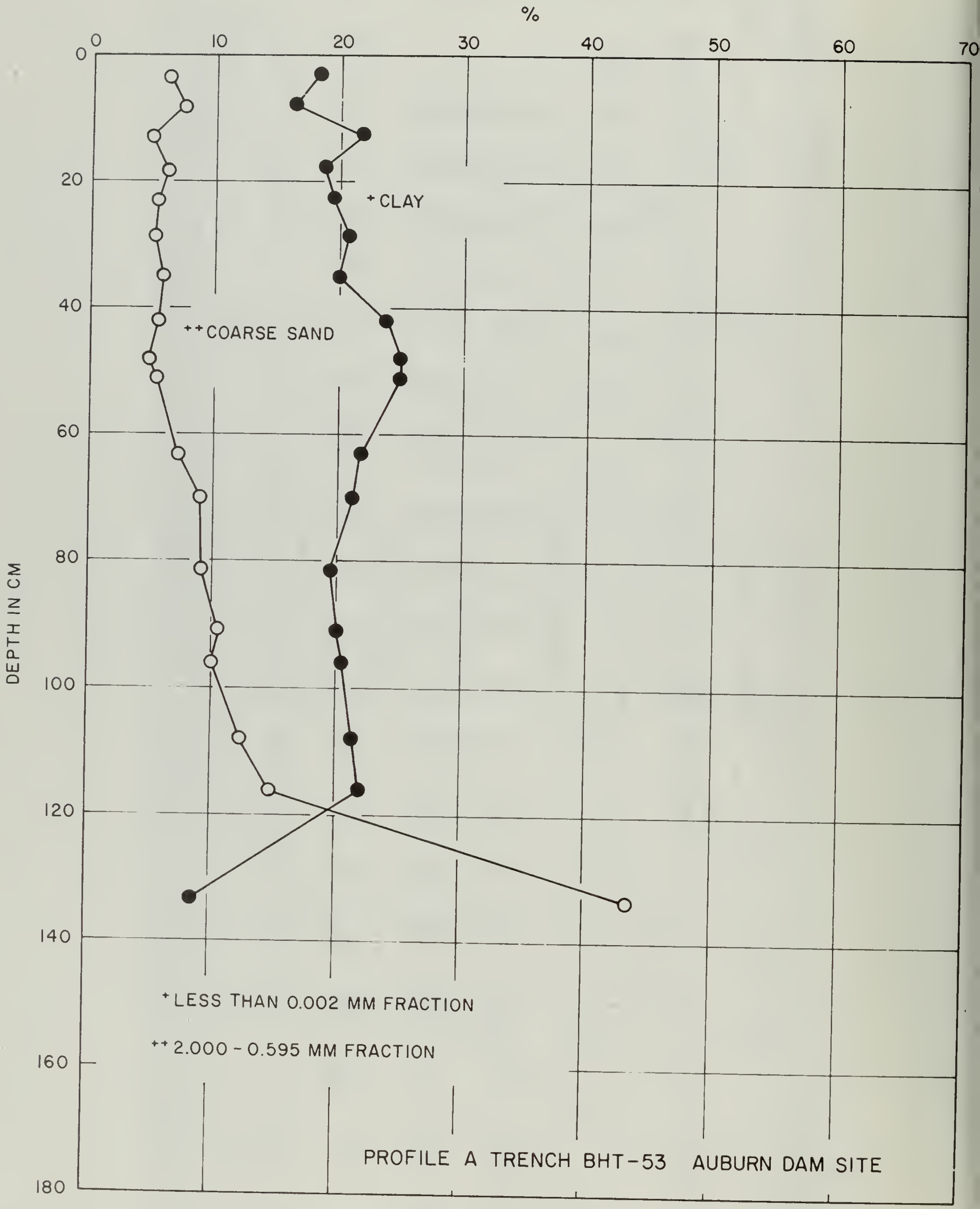

Figure 2a. Depth function for coarse sand and clay contents in profile A.

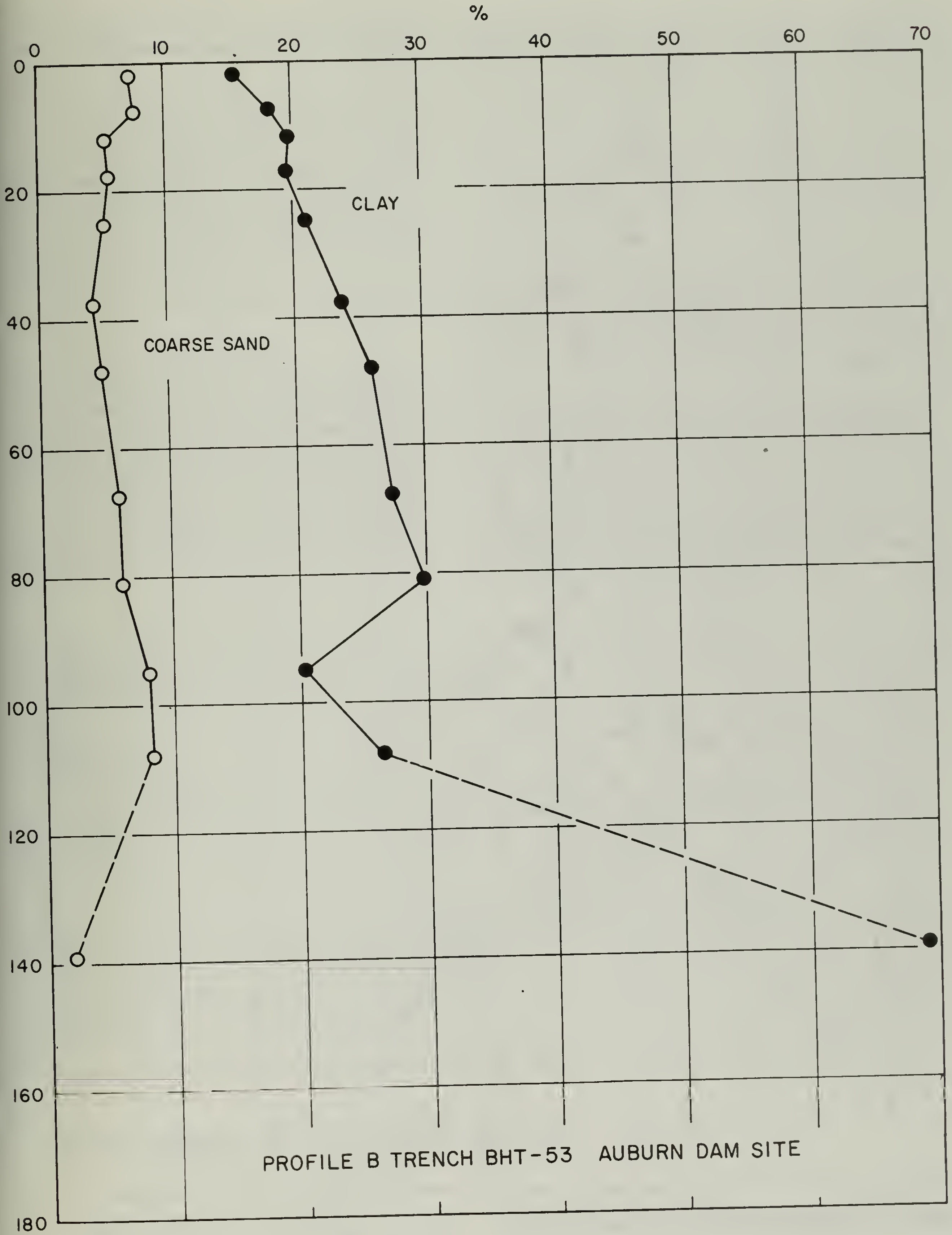

Figure 2b. Depth function for coarse sand and clay contents in profile B.

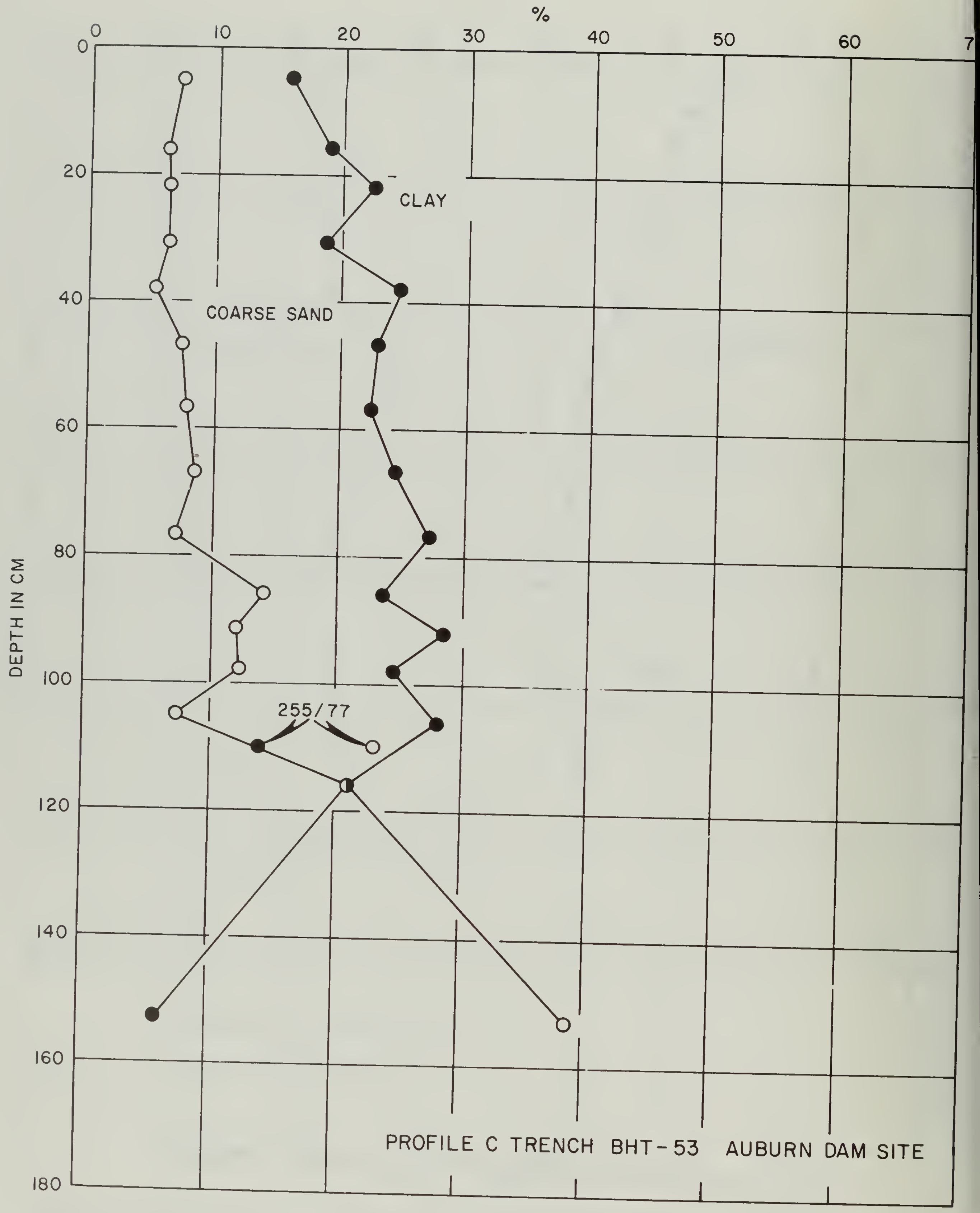

Figure 2c. Depth function for coarse sand and clay contents in profile C.

sturbance following an initial period of *in situ* weathering. In .e Mehrten conglomerate, weathering tends to produce fragile, prolitic cobbles that crumble into fragments at the slightest uch.

Significantly, angular orphans occur only in the upper, col- vially–derived soil horizons of the conglomerate. The saprolit- rocks often appear confined to residually–derived horizons. he depth at which these saprolitic rocks were encountered was nsidered the "saprolite boundary" (Figure 3). In trench BHT 53 the boundary occurs at 55 cm, and in trench BHT–70 it curs at 32 cm. The thickness of the colluvial unit in BHT–70 thus limited to no more than 32 cm. This is to be expected, r the slope is only two to four degrees (Shlemon, 1977a, p. 35). dditionally, there is very little material upslope from the site at would contribute to colluviation.

OIL IN SANDSTONE

The depth of colluviation is easier to detect in soils developed n sandstone than in those developed on conglomerate. This is ecause in the Sierra foothills the sandstone underlying colluvi- m is generally marked by a pronounced stoneline (Borchardt, ice, and Taylor, 1980), as evidenced in the sandstone exposure trench ST–68 (Figures 4 and 5). Here the stoneline conforms the modern topography and occurs at about one meter depth. his is considered more or less a maximum for the thickness of he colluvial unit on the Mehrten Formation. The sandstone, of ourse, was more easily eroded than the conglomerate on similar 4 degree slopes.

The soil profile in the sandstone exposed in trench ST–68 appears to contain a relict paleosol beneath the stoneline (Figures 4, 5, 6, and 7). An analysis of the fine soil material (less than 2 mm particles) confirms that normal soil development has occurred in the colluvium (Table 1 and Figure 7). For example, the clay content increases with depth while the silt content decreases slightly. In addition, there appears to be little difference between the fine materials in the B2 and IIB2 horizons. The Roman numeral designation "II" is appropriate only in the sense that the IIB2 horizon contains cobbles and the B2 horizon does not. Thus, it appears likely that the entire colluvial unit above the 100 cm depth is the result of a single erosive episode of initial high intensity.

The paleosol development apparently proceeded along similar lines (Figure 7). Clay contents increase and silt contents decrease with depth below the stoneline. Perhaps this indicates that the IIIB3b horizon (b for "buried") should be more correctly designated a IIIB1b horizon. The fact that the IIIB3b horizon contains more clay than the IIIB2b horizon also supports this contention. Clay has obviously translocated to the IIIB3b horizon.

The question arises as to how much of this paleosol is not significantly affected by modern soil weathering. In general, soils on nearly level sites in the Mehrten conglomerate weather to depths of less than a meter (Shlemon, 1977a, p. 34–45). If this is the case for this site, then the bottom of the stoneline at 100 cm marks the boundary between two soil profiles of contrasting soil development. Certainly, much of the clay beneath the stoneline has formed *in situ* during a period of time extending back to a previous erosive period that may have occurred as much as

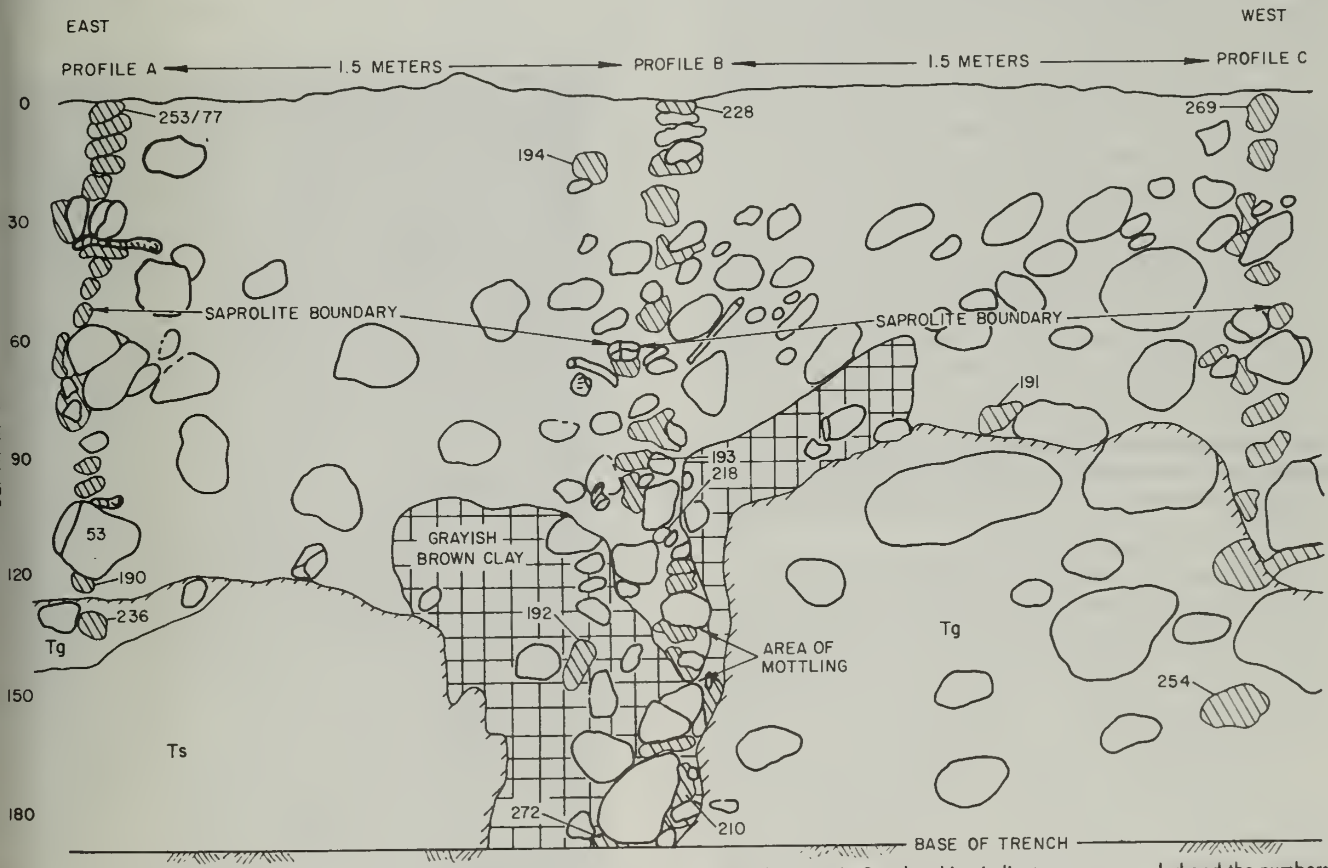

Figure 3. Log and locations of soil profiles A, B and C above the Maidu East shear in trench BHT–53. Crosshatching indicates areas sampled and the numbers indicate CDMG laboratory numbers (1977). The boxed area is the gray brown "pseudopaleosol". The saprolite boundary is the minimum depth at which saprolites occur.

Figure 4. Stoneline at the base of the colluvium on the eroded sandstone scarp exposed in trench ST–68. The stoneline occurs at one meter depth.

Figure 5. Oxidized soil developed under good drainage in colluvium and sandstone of the Mehrten Formation at trench ST–68. This soil contains only halloysite in the clay fraction. The stoneline is a pronounced feature of colluviation in the Sierra Nevada foothills.

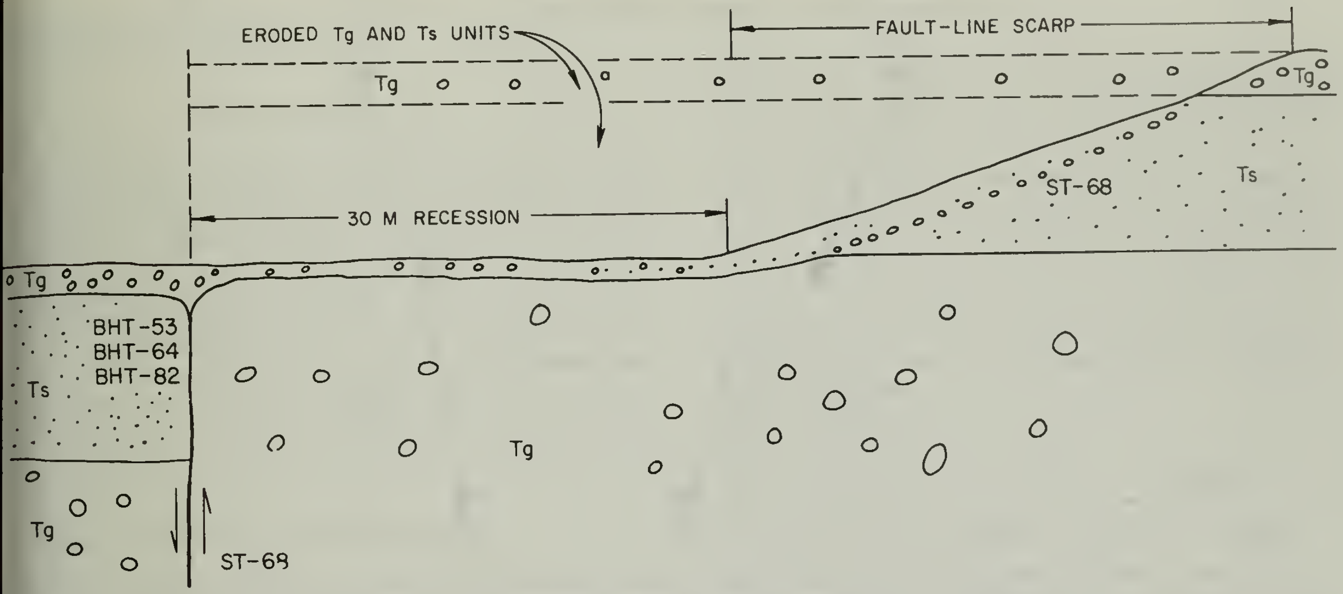

Figure 6. Cross section showing a fault–line scarp and its relationship to early faulting in sandstone (Ts) and conglomerate (Tg) of the Mehrten Formation at trenches ST–68, BHT–53, 64 and 82.

130,000 years ago (Borchardt, Rice, and Taylor, 1980). The clay content in the IIIB3b increased to 35 percent mostly as a result of weathering in sandy bedrock (IIIC) containing 10 percent clay. On the other hand, the soil development above the stoneline appears to reflect a mere rearrangement of the clay contents within a more or less uniform colluvial unit originally derived from IIIB2b–type residual soils upslope. This site is one of the most favorable for clay illuviation, and yet the A1 horizon still contains 20 percent clay while the B2 horizon has only 32 percent. This fact and many others support a Holocene age for the colluvial unit characteristic of this site and most others throughout the foothills (Borchardt, Rice, and Taylor, 1980).

Microscopic observations of sand fractions showed little difference in the extent of weathering between the soil above the stoneline and the paleosol below it. A similar conclusion was drawn by Swan and Hanson (1977, p. B–42) for heavy mineral etching elsewhere in the Foothills colluvium. They state that "The anomalously high degree of etching observed in the younger colluvium is due to contamination with reworked grains that were derived from older deposits and soils" (p. B–42). At ST–68, both the colluvium and the paleosol have sand fractions that contain aggregates of feldspars and heavy minerals encased within a matrix of slightly to moderately weathered glass. The degree of weathering of this glassy matrix is much less than that of a rare remnant of old Mehrten–derived colluvium in trench ST–107 (Figure 8). The old colluvium in ST–107 might represent material deposited perhaps as much as 130,000 years ago during a previous post–glacial erosive period. The contrast between this remnant and the less weathered soils that characterize the present Mehrten surface is particularly instructive.

SOIL ON AN OLDER MEHRTEN–DERIVED COLLUVIUM

Trench ST–107 exposes a 12 m wide landslide or gully fill of dominantly Mehrten colluvium (Figure 8) that is considerably older than any of the colluvial deposits or soils that cover most of the Mehrten conglomerate (see Frei and others, 1977, Drawing no. 7305). This deposit is easily distinguished by its reddish brown or dark reddish brown color (2.5YR4/4d, 3/4m) and the clay loam texture of the less than 2 mm soil (Table 2). This contrasts with the more recent colluvium at the site which is dark yellowish brown (10YR4/6m) and silt loam in texture.

The clay content of a sample of the older colluvium was only 28 percent (Table 2). This low value is more or less comparable to the values found for other well–drained Mehrten soils. The fact that a trace of beidellite is present (Table 2) also may indicate that the colluvium is derived from soils whose age is more like 100,000 B.P. (years before present) than 500,000 or 1,000,000 B.P. Beidellite is a mineral usually derived from 2:1 layer silicates present in existing rocks. Given enough time, beidellite is destroyed under severe leaching conditions such as at this site. The younger colluvium at this site contains mica, montmorillonite, and vermiculite in addition to halloysite (Table 2). It also contains about 60 percent silt and less than 18 percent clay. These data indicate that the colluvium here is a mixture of materials derived from the metasedimentary bedrock as well as from the Mehrten Formation which crops out about 23 m upslope.

Examination of the sand fraction of the older colluvium revealed a degree of weathering easily distinguishable from any of the other weathered samples from the Mehrten Formation. Even so, the highly devitrified matrix of these sand particles still holds individual crystals of feldspar and heavy minerals. The sand probably is derived entirely from tuffaceous matrix material rather than from disintegration of andesitic cobble. As mentioned previously, this degree of weathering might represent pre–Wisconsin 75,000 B.P. or Illinoian soil formation.

The deposit underlies the stoneline at the base of the more recent colluvium that we have tentatively correlated with the early Holocene pluvial period (Borchardt, Rice, and Taylor, 1980). Perhaps, this older colluvium was deposited during a similar pluvial period following the Illinoian glaciation ending about 130,000 B.P. This appears likely because the older colluvium fills a gully that was once part of a presently inactive drain-

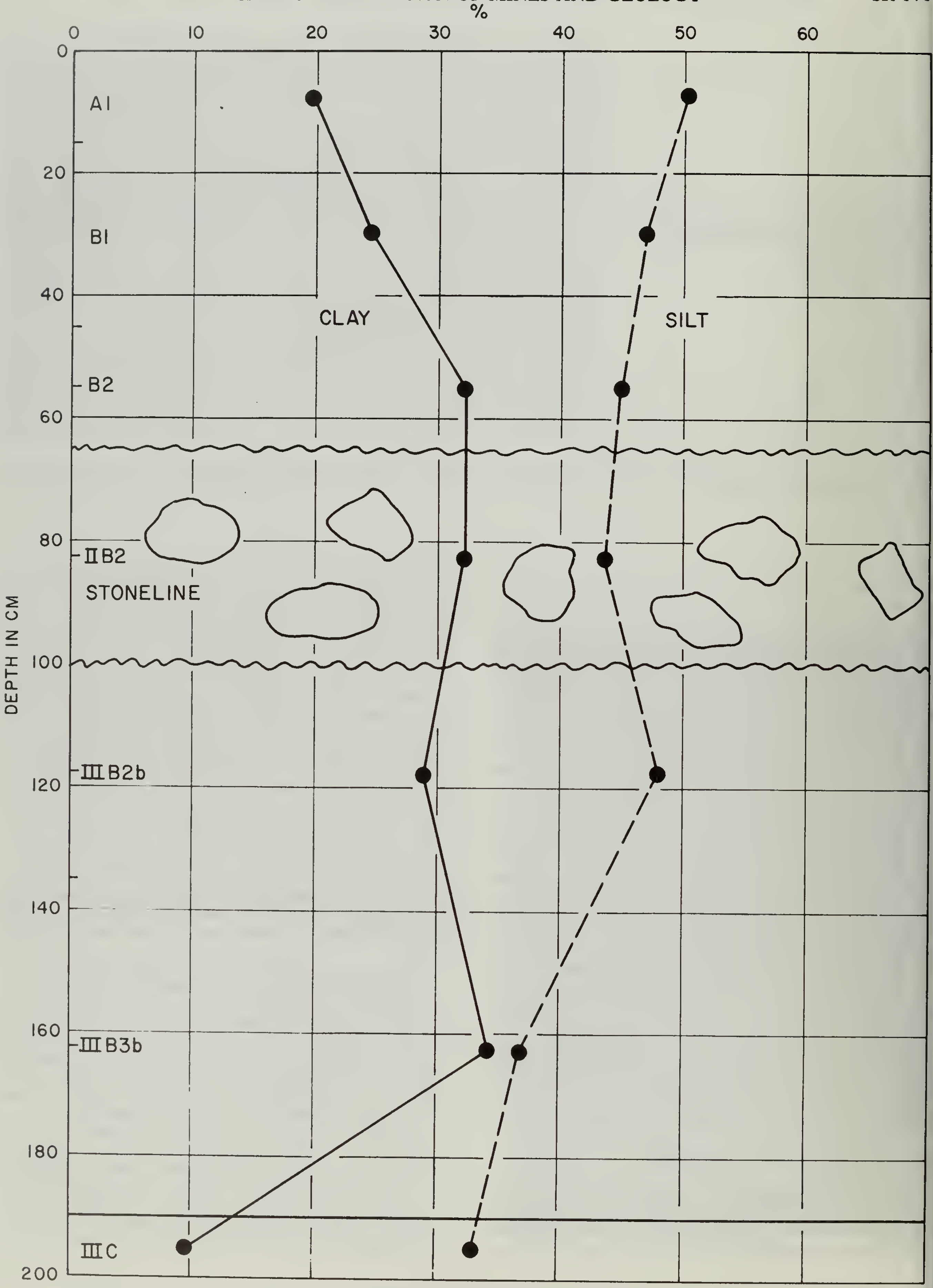

Figure 7. Clay and silt depth functions illustrating the lithologic discontinuity in the soil developed on Mehrten sandstone in trench ST–68 (see also Figure 5).

age system. Current drainage is handled by a similar-size gully about 38 m to the west.

Poorly Drained Soils

There are two somewhat related types of soil formed under poor drainage conditions. The first we call a humic gley soil (Soil Survey Staff, 1975), because in it can be seen the effects of poor drainage associated with the modern surface, as in trench BHT-66. Strictly speaking, the second is not actually a soil; it occurs at considerable depth in trench BHT-69, but under perched water conditions similar to that of the humic gley soil. As we have seen, the Mehrten Formation is, for the most part, well drained. Poor drainage is likely to occur only under special conditions (see, for similar example, Thordarson, 1965; Wilson and Emmons, 1977). These conditions occur in a spring area associated with the Maidu East fault zone near the field offices (Figure 1).

HUMIC GLEY SOIL IN TRENCH BHT–66

Humic gleys are soils developed under low redox potentials. The iron in these soils remains primarily in the reduced form. Thus, the predominant color is the original gray of most minerals. In most soils, yellowish and reddish colors indicate the presence of oxidized forms of iron, high redox potentials, and a certain degree of good drainage.

The humic gley profile in the west end of trench BHT–66 is developed in a number of materials derived from the Mehrten Formation (Figure 9). First, about a meter of artificial fill has been added to the soil to construct a shoulder for the asphalt highway between the trench and the U.S.B.R. Field Offices. Second, a 56 cm thick brown (10YR5/3d, 2/2m) A1 horizon of silt loam texture occurs immediately beneath the fill. Third, a light brownish gray (2.5Y6/2d, 4/2m) IIB1bg horizon (g is for 'gleyed') containing a few cobbles and gleyed soil of clay loam texture is buried by the A1 horizon. Fourth, a light gray (5Y7/1d, 5/2m) IIB2bg has slightly more clay and considerably more cobbles than the otherwise similar horizon above it. Fifth, a light gray (5Y7/1d, 4/2m) IIIB2bg clay horizon occurs beneath the cobble and has developed *in situ* at the top of a bed of Mehrten sandstone.

A1 horizon

The A1 horizon, unlike all the other horizons at this site, contains no detectable montmorillonite; and, therefore, the clay minerals in this horizon did not form under the present poor-drainage conditions (Table 1, Figures 10 and 11). Because halloysite is the only detectable clay mineral in this unit, we consider the A1 horizon to be colluvium derived from well-drained soils upslope (Singer and Navrot, 1977). Another indication of the colluvial origin of the A1 horizon is its coarse sand/fine sand (cos/fs) ratio of 0.55 (Table 1). This contrasts with ratios of less than 0.34 in the horizon below. Normally, soils developed in the Mehrten Formation have cos/fs ratios that decrease with nearness to the soil surface (Figure 12). This is because the large aggregates of glass-bound phenocrysts tend to diminish in size as weathering proceeds. In effect, the high cos/fs ratio of the A1 horizon may indicate that it is colluvium derived from soil horizons that are less weathered than the IIB1bg and IIB2bg horizons at the site. The only other site on the Mehrten Formation where cos/fs ratios increased with nearness to the surface was at ST–68 (Table 1). Here, the cos/fs increased from 0.22 to 0.37, but only in the top 15 cm.

IIB1bg and IIB2bg horizons

The discussion of the next two horizons depends upon a very critical assumption. This assumption is that the material between 56 and 110 cm beneath the fill is Mehrten conglomerate and not a layer of older Mehrten colluvium. Questions could arise about this because the unit is so thin. Significantly, the cobbles in this unit are well-rounded as they appear in Mehrten conglomerate elsewhere (Figure 9). Angular fragments separated from their derivative cobbles were undetected. Also, reducing conditions here produce etched surfaces on cobbles rather than the oxidized rinds common in well-drained areas. This would further support a residual origin for the unit. On the other hand, the geologic log of the west end of this trench shows no indication of Mehrten conglomerate at this depth (Frei and others, 1977, Drawing no. 7359). However, Frei and others (1977) were not convinced that the thick cobbly unit was entirely colluvium (Figure 13). In BHT–69 the Mehrten sandstone is overlain by 150 cm of oxidized, Mehrten-derived colluvium or conglomerate. The lower 50 cm of this colluvial unit is queried and described as: "Rounded gravel with cobbles in matrix or red brown clayey sand and sandy clay. Scattered to frequent roots. Cobbles intensely weathered with weathering rinds" (Figure 13; Frei and others, 1977, Drawing no. 7356).

In any case, it seems clear that Holocene colluviation was confined to the A1 horizon. The cobbly unit represented by the IIB1bg and IIB2bg contains small amounts of spruce, hemlock and other pollen indicative of a cool-weather period according to Kilbourne (1978). The unit must have been accessible to pollen rain and its preservation during a glacial period. Thus, it must be at least 11,000 years old, and very likely, clays have been forming within it throughout the Wisconsin glacial episode that began at least 75,000 years ago.

The clay content of the IIB1bg horizon was slightly less than the content in the IIB2bg horizon (Table 1). Likewise, the peak to background ratio for the 7.2A x-ray peak of halloysite was 24 percent greater for the IIB2bg than the IIB1bg (0.89 vs 0.72, Table 1). Also, the 17A x-ray peak for montmorillonite was 40 percent greater in the IIB2bg than in the IIB1bg horizon. These data, though not as quantitative as implied (Borchardt, 1977a, p. 321), show that the unit has undergone the effects of weathering or clay translocation.

The presence of montmorillonite at this site is, of course, expected because of its poor drainage conditions (Borchardt, 1977a, p. 306). The andesitic volcanic rocks of the Mehrten Formation provided large amounts of silica and bases needed for montmorillonite precipitation from soil solutions. In well-drained soils silica and bases are leached away, but under poor drainage, they accumulate. Thus, we see x-ray evidence for montmorillonite in both the IIB1bg and the IIB2bg horizons but not in the colluvially-derived A1 which has not been in place long enough for it to form (Figure 11). Halloysite also exists in these older horizons. Most likely, it has formed from feldspars (Sand, 1956) under poorly drained conditions as described for Oregon soils (Dingus, 1973, p. 62; Dudas and Harward, 1975). The latter study shows that halloysite can form within 6,600 years, but implies that montmorillonite may require additional time. Although halloysite occurs or forms under both good and poor drainage conditions on the Mehrten Formation, montmorillonite does not. If the Oregon work is applicable here, the presence of montmorillonite indicates that the IIB1bg and IIB2bg horizons have been weathering for significantly longer than 6,600 years. The latter, of course, is also confirmed by the presence of the overlying colluvial unit of early Holocene age (Borchardt, Rice and Taylor, 1980).

Figure 8. Deposit of older Mehrten–derived colluvium or landslide in an abandoned drainage channel in trench ST–107.

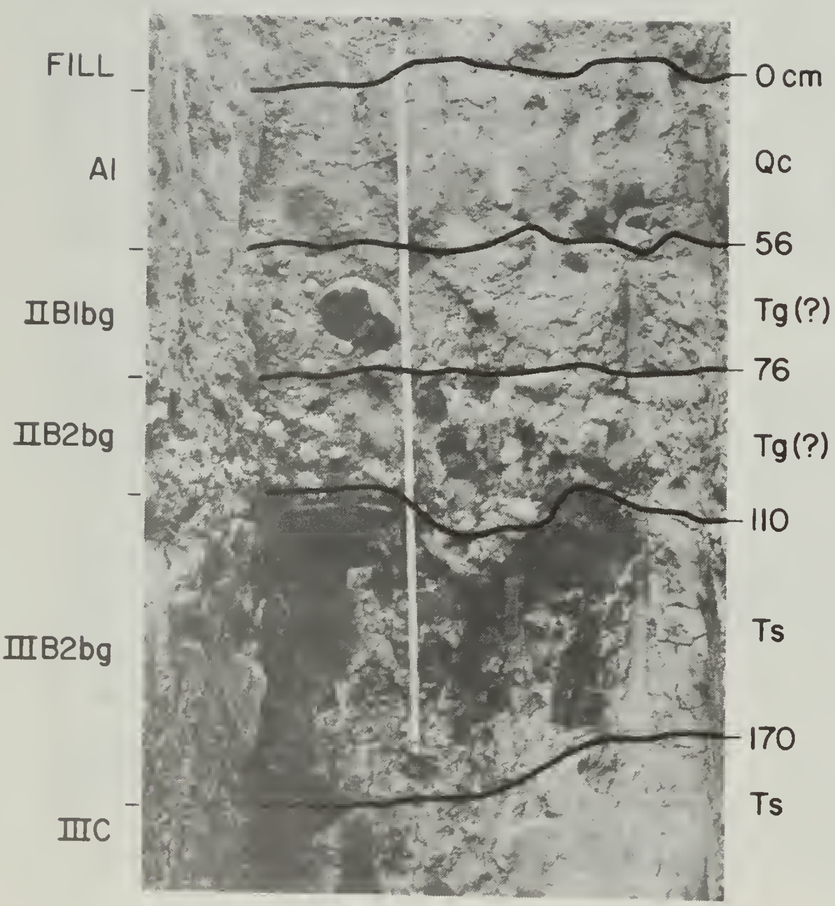

Figure 9. Humic gley developed under poor drainage in colluvium, conglomerate (?), and sandstone of the Mehrten Formation at trench BHT–66. This soil contains halloysite in the A1 horizon and both halloysite and montmorillonite in the B horizons.

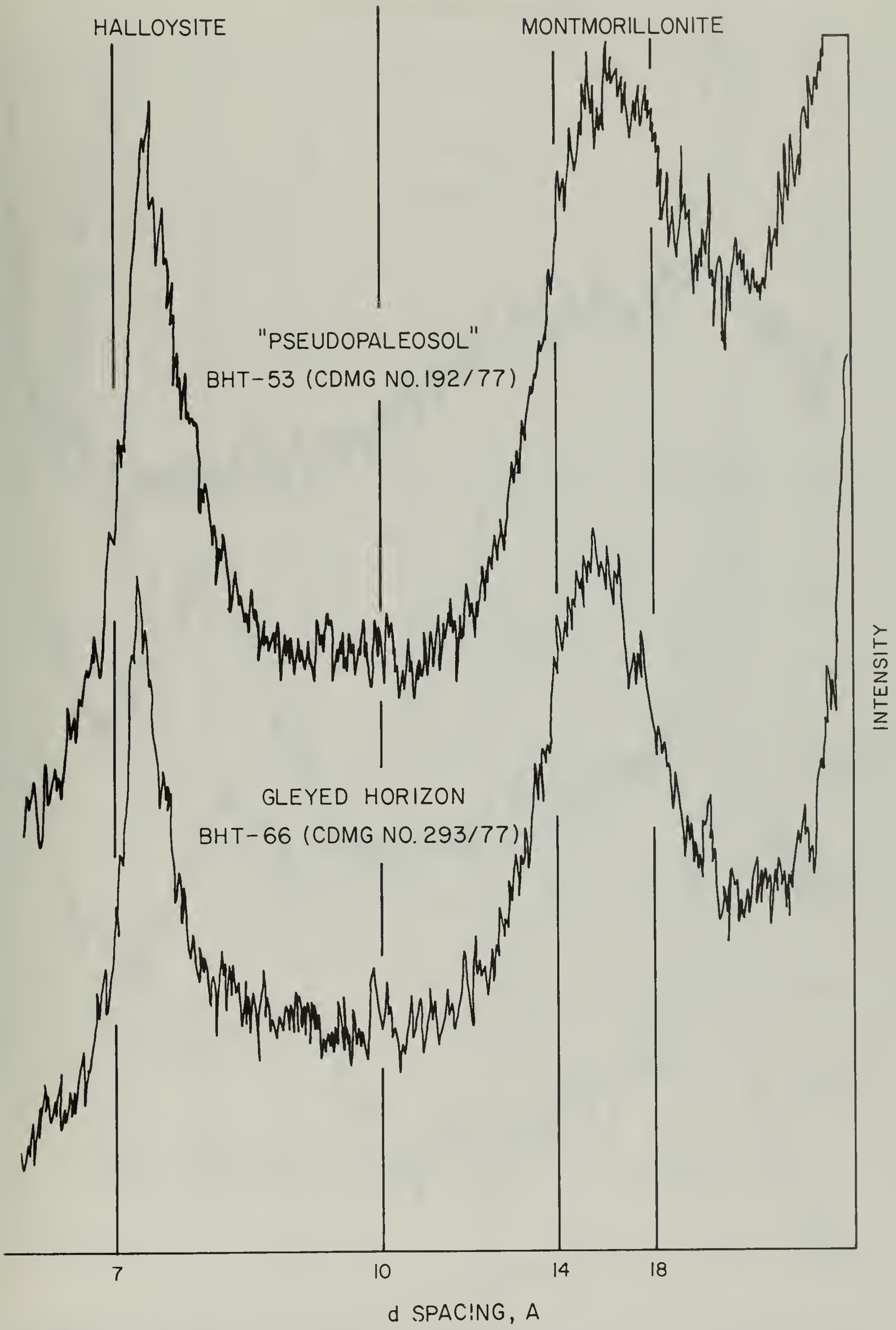

Figure 10. X-ray diffraction patterns comparing the "pseudopaleosol" at BHT-53 with the humic gley at BHT-66.

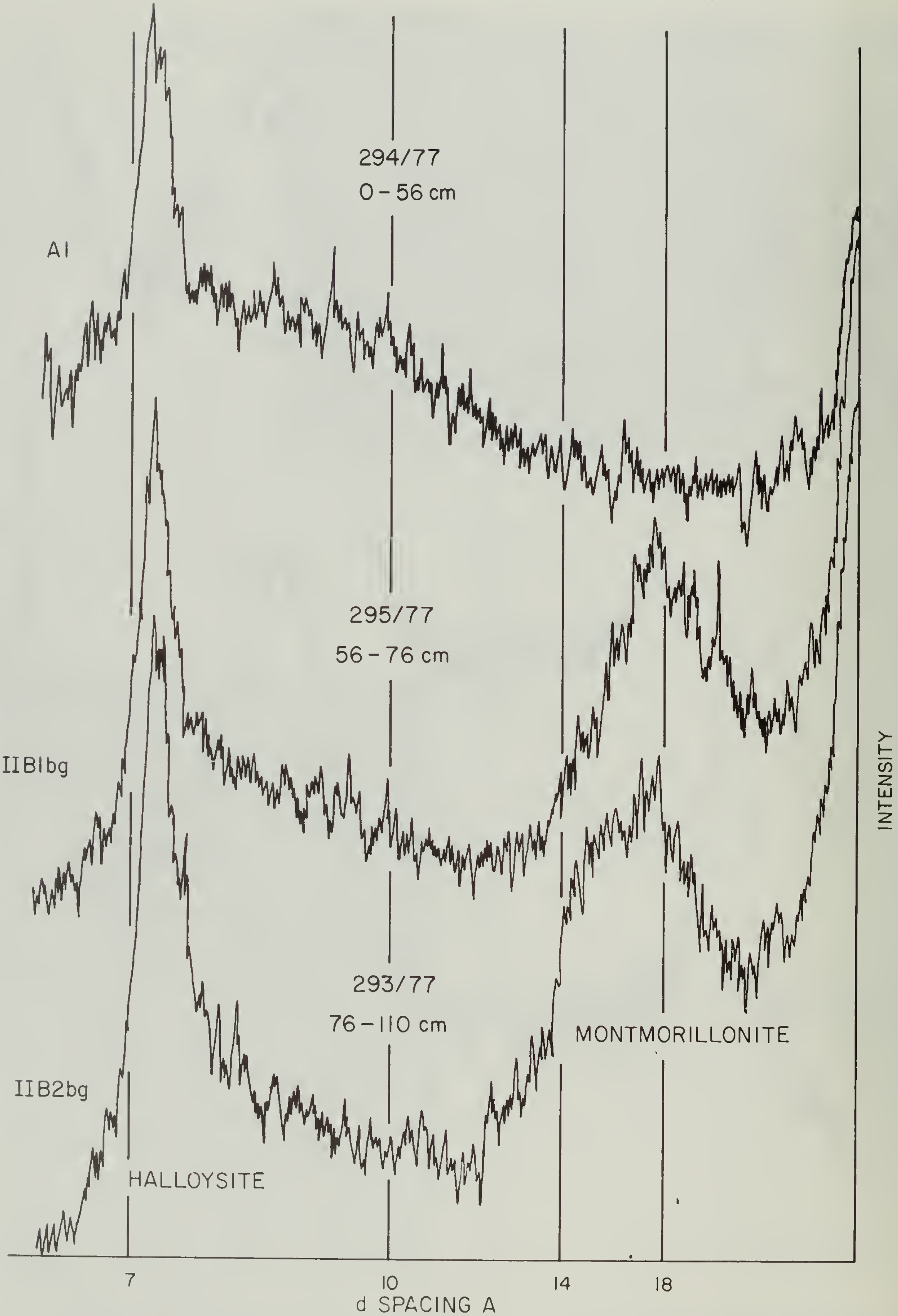

Figure 11. X–ray diffraction patterns illustrating the formation of montmorillonite under poorly drained conditions at trench BHT–66 (Mg saturated, glycerol vapor).

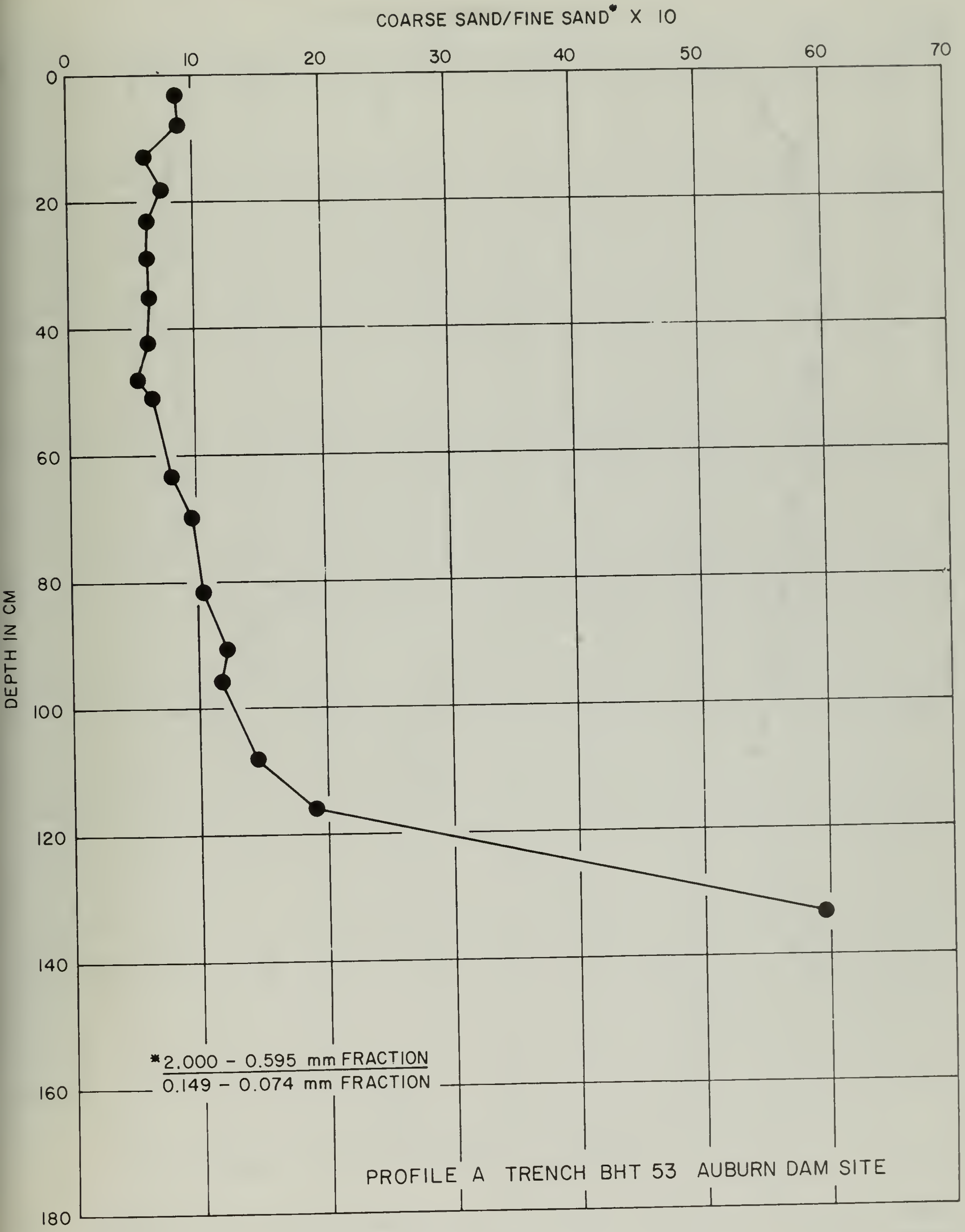

Figure 12a. Depth function for coarse sand to fine sand ratios in profile A.

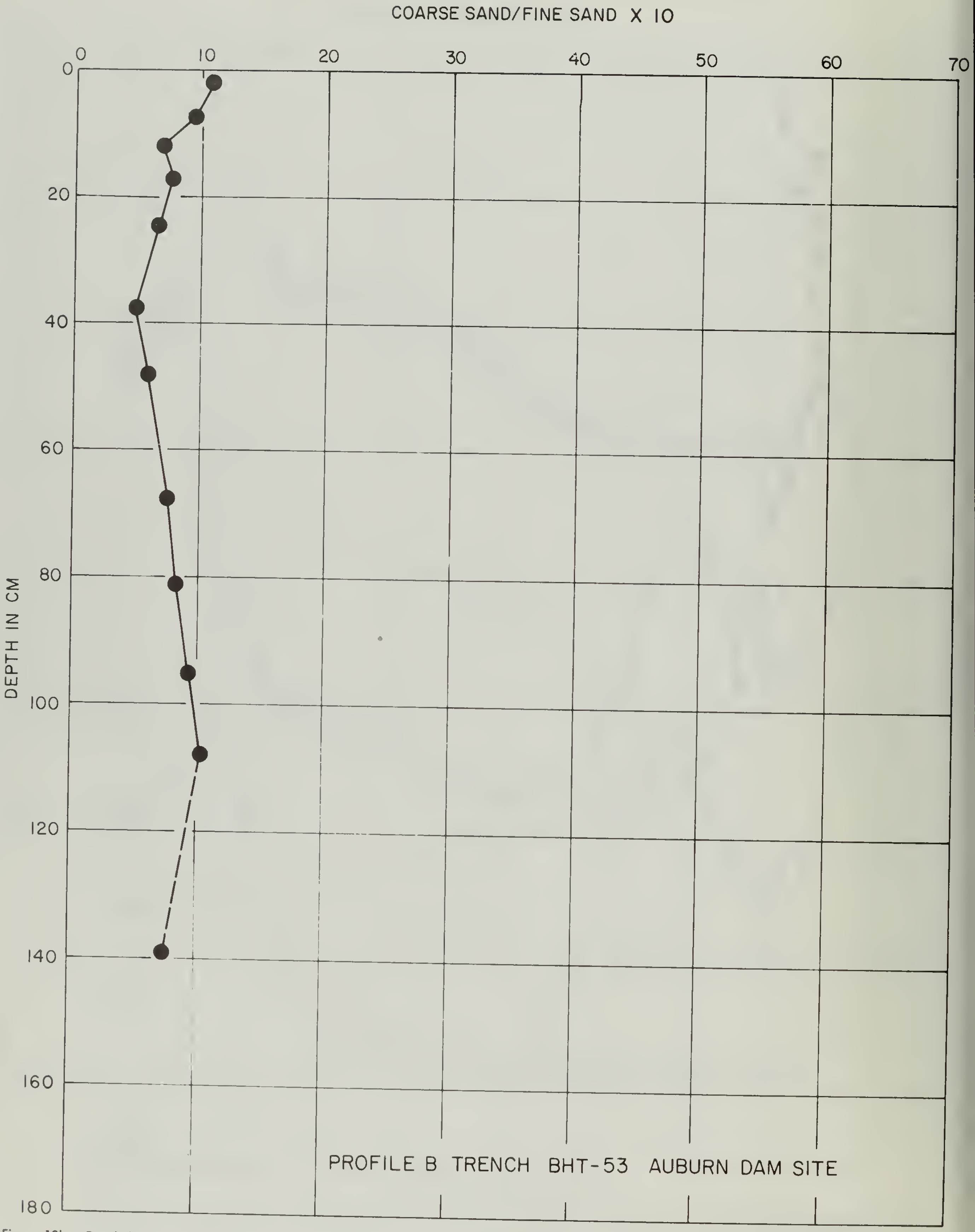

Figure 12b. Depth function for coorse sond to fine sond rotios in profile B.

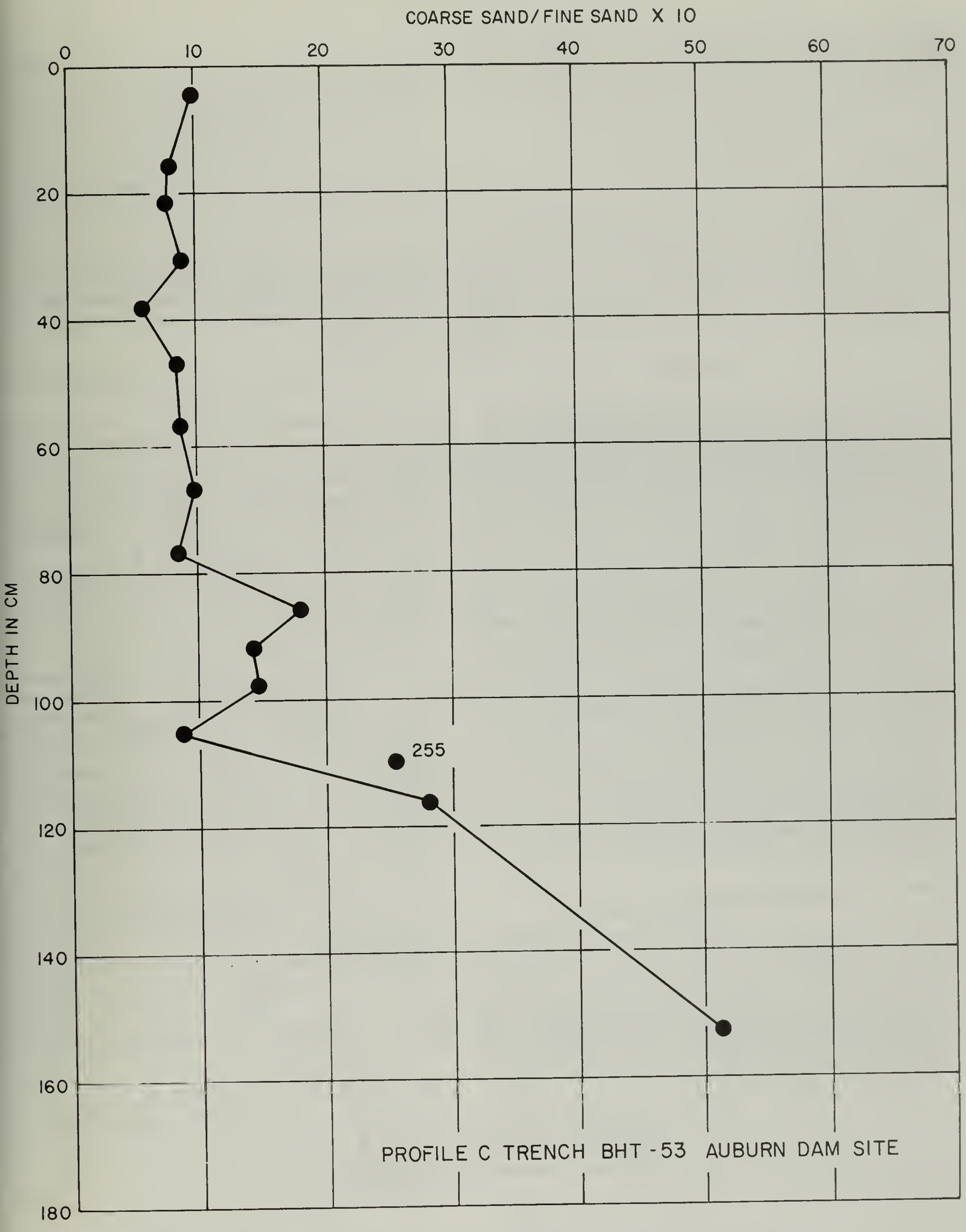

Figure 12c. Depth function for coarse sand to fine sand ratios in profile C.

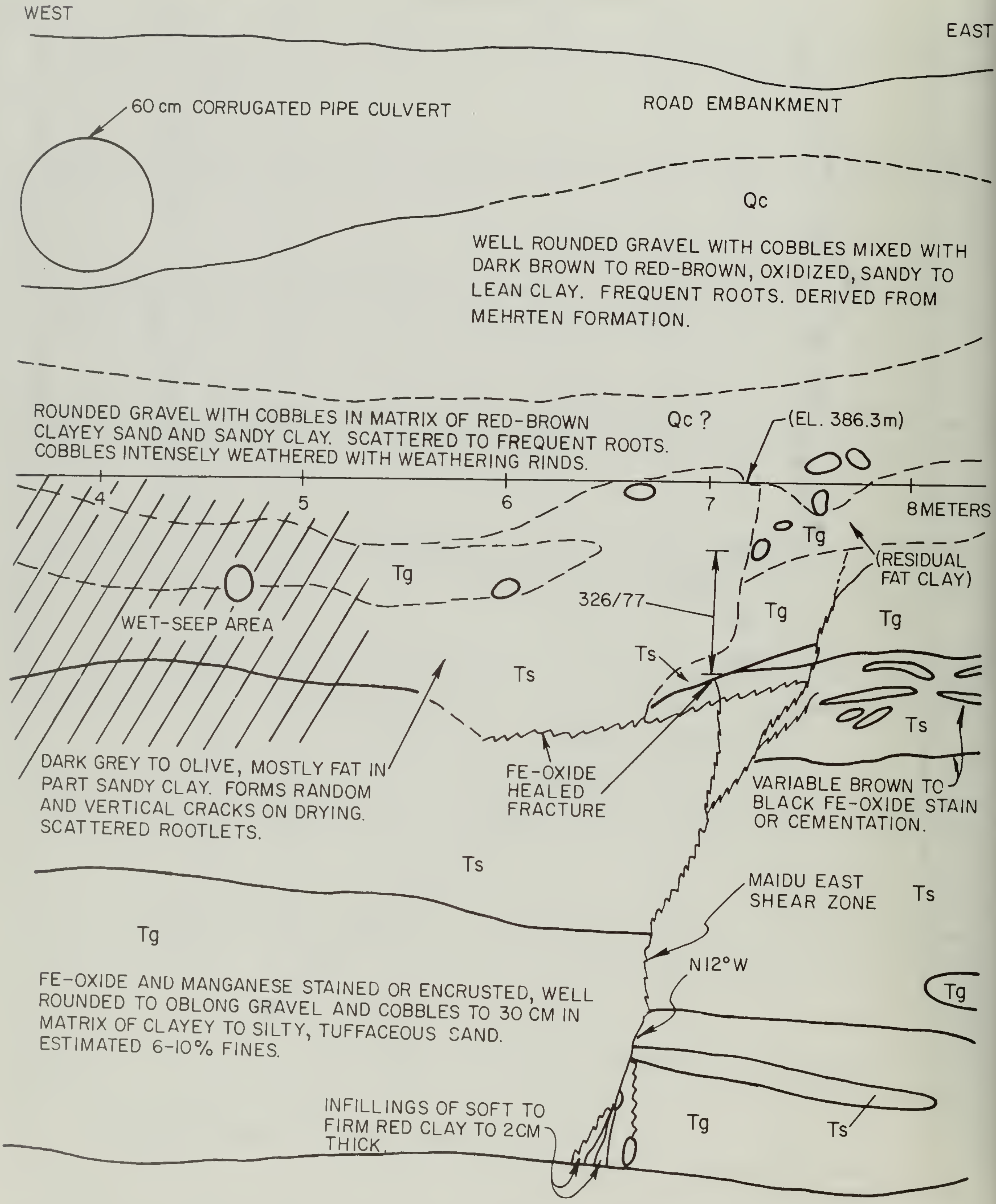

Figure 13. Log of north wall of trench BHT–69, modified from Frei and others (1977, Drawing no. 7356), showing a shear in the Maidu East fault zone and its relationship to the gleyed horizon represented by CDMG No. 326/77. The right abutment of the proposed Auburn dam is 284 m to the north (N8°E).

2bg horizon

The IIIB2bg horizon has developed in a Mehrten sandstone t beneath the colluvium (Figure 9). The lithologic boundary ween the IIB2bg and the IIIB2bg horizons is very distinct. r example, there was 15.5 percent gravel in the IIB2bg horizon none in the IIIB2bg horizon (Table 1).

The clay content of the IIIB2bg horizon was 48.6 percent. is sandstone–derived horizon had 50 percent more clay than conglomerate–derived horizons. Likewise, the peak/background ratios of halloysite and montmorillonite x–ray peaks are to 40 percent greater in the sandstone than in the conglomer- (Table 1). This reflects either illuviation from upper horis, the fine particle size, or considerably greater duration of l weathering. More detailed sampling—for example, at 5 cm ervals—might help us decide which of these possibilities minates.

ONTMORILLONITE FORMATION IN TRENCH BHT–69

Trench BHT–69 (Figure 13) lies 38 m south of BHT–66 igure 1) on the southernmost edge of the spring area near the ld Offices. This trench exposes a 60 cm offset in the Mehrten rmation. As previously stated, this trench contains 150 cm of idized colluvium or conglomerate overlying a gleyed horizon ich is very similar to the IIIB2bg horizon in trench BHT–66 able 1; Figure 9). The gleyed horizon is developed primarily a Mehrten sandstone unit. The thickness of the gleyed portion pears to decrease with distance from the center of a gully sently occupied by a 60 cm corrugated pipe culvert (Figure ; Frei and others, 1977, Drawing nos. 7356 and 7357). The yed portion appears widest on the north wall of the trench, ere it extends for a distance on either side of shears in the aidu East fault zone.

There are no obvious slickensides that would indicate fault vement since the genesis of the gleyed horizon. However, cent movement cannot be ruled out entirely because, like the leosol in BHT–66, the clay fraction contains montmorillonite able 1). Montmorillonite expands and contracts with changes moisture content (Figure 13), possibly destroying evidence r fault movement. However, it is unlikely that much seasonal ange in moisture occurs at this depth (180–240 cm). Even so, n oxide coatings appear in healed fractures overlying the aidu East shear (Figure 13). These coatings could develop ly through localized increases in redox potential that are usuly associated with improvements in drainage (Wilson and Emons, 1977, p. 697). It is as if the area now receives slightly less oisture than it did during the period (Wisconsin?) when most the montmorillonite was forming. The iron oxide containing actures may have formed due to shrinkage following a slight wering of the "permanent" water table.

Changes in redox potential are indicated elsewhere in this ench. Variable brown to black iron–manganese oxide stains cur in the upper 50 cm of a sandstone bed overlain by conlomerate on the east side of the shear (Figure 13). This kind f stain development also occurs in a bed of conglomerate eneath the gleyed sandstone to the west of the shear. A wet seep rea occurs above this unit engulfing the entire gleyed horizon t this point. For the most part, the thickness of the gleyed orizon appears to diminish with distance from the seep area. It lso diminishes with distance upslope and, in this respect, apears to conform to the modern drainage pattern.

Infillings of red (or brown) clay occur within the shear zone t depth (4.5 m, Figure 13). This highly oxidized clay may have een deposited in shear fractures by translocation from soils (Shlemon, 1977a, p. 27). If so, this must have occurred prior to the development of the gray–colored, gleyed horizon that now appears to block translocation of oxidized clay. The formation of montmorillonite in gleyed sections of this trench, thus, postdates the earliest faulting of the Mehrten Formation.

COLLUVIATION

Colluviation on the Mehrten Formation is important for a number of reasons. First, the bottom of a colluvial unit is the contact between young transported material and an older surface that might be considered a datable unit. Second, the age of a colluvial episode gives a minimum age for the paleosols underlying it. Third, colluviation can destroy fault scarps and other evidence of tectonic activity.

Stonelines

Stonelines indicate a period of high energy erosion (Ruhe, Daniels, and Cady, 1967, p. 61; Ojanuga and Wirth, 1977). As such, they often are correlative with a climatic change that may or may not be part of the known climatic record. In the Sierra Nevada foothills, we have noticed a relatively systematic occurrence of a stoneline or coarse colluvium at the base of the most recent colluvial deposits. This is especially well illustrated in trench ST–68 where the stoneline overlies a moderately developed paleosol formed in sandstone of the Mehrten Formation (Figures 4 and 5). The colluvial unit at this site conforms to the present land surface. There have been speculations that the colluvial episode represented by the stoneline may be related to soil erosion during the last glaciation. Through evaluation of argillic horizon development in Mehrten–derived soils, Shlemon (1977a) implies that the stoneline in ST–68 is at least 75,000 B.P. Others (Denis Marchand and Bert Swan, oral communication, August 1, 1977) have suggested that the stoneline in ST–68 has an age somewhere between 9,000 and 17,000 B.P. Borchardt, Rice, and Taylor (1980) have presented the case for a 9,000 B.P. age for the Foothills colluvium. This controversy is important because the unit appears correlative with the colluvium that overlies paleosols throughout the foothills. If the Foothills colluvium is Holocene in age, then the paleosol was probably an active soil during Wisconsin time.

Fault–line Scarp on Sandstone

The Maidu East fault was originally located by using air photo interpretation of lineaments (Schwartz and others, 1977). The Maidu East lineament was especially well defined by a rapid change in elevation on the slope above trench BHT–53. This feature was later shown to be a fault–line scarp in a sandstone bed that occurs about 30 m west of the actual fault break along the Maidu East fault zone (Figures 1, 4, and 14; Frei and others, 1977, Drawing nos. 7353 and 7352). This scarp has implications for the age of earliest faulting on the Mehrten Formation.

We propose that the sandstone bed exposed in ST–68 (Figures 4 and 6) is an erosional remnant of the sandstone unit in BHT–53, 64, 82, and 106 (Figure 1). Evidence compiled from measurements on an offset lahar in ST–68 and 20 to 40 degree striations in ST–91, indicate an apparent 5.2 m vertical offset with as much as 9.3 m of right lateral offset along the main shear.

It appears that the sandstone unit may have been capped by only a thin veneer of more resistant conglomerate at the time of the first faulting of the unit. This veneer is represented by the conglomerate overlying the sandstone unit on the east side of the fault (Figure 6). Once the thin veneer of conglomerate was eroded away, the sandstone, being much less resistant, would form an eroded scarp as it does in ST–68 (Figure 4). The recession of this 14 degree scarp has proceeded for a distance of 30 m, and thus, it is a "fault–line" scarp. This amount of erosion must have occurred over a period of hundreds of thousands of years. As previously mentioned, the scarp has a moderately developed soil and stoneline at about one meter depth in trench ST–68.

The erosion of this sandstone unit explains the relatively level surface between the scarp and the Maidu East fault of BHT–53, 64, 82, and 106. An accumulation of boulders here also may be remnants of erosion (or, less likely, mining activity) at this locality.

The argillic horizon in trench BHT–106 is only weakly developed, and the R horizon appears unweathered, particularly on the west side of the main shear in the fault zone. We would resign ourselves exclusively to "mining activity" to explain these features except for one other observation—the presence of a "pseudopaleosol" over the shear zone. This occurs at a depth of about 50 cm and in no way could have developed since mining was prominent in the area. Re–oxidation of the upper portion of the "pseudopaleosol" also indicates that much of the original soil has been eroded away. Perhaps this soil represents the type of development we might expect on the Mehrten Formation in those areas where the soil and colluvium was completely stripped during the last major erosive eposide possibly 9,000 years ago.

Another weakly developed soil occurs in the Mehrten conglomerate at the edge of a roadcut in Maidu Drive. This locality occurs just as the highway approaches the southeastern corner of the main lahar unit that caps the conglomerate about 425 m N60°W of BHT–106. This site also contains a scarp, but this time it is the eroding edge of the lahar unit that is possibly responsible for the preservation of the Mehrten Formation in the area. These indications of relatively young soil development need further evaluation. Perhaps this would be useful for soil "calibration" (Shlemon, 1977a, p. 36) on the Mehrten Formation.

Lithologic Change Over the Maidu East Fault Zone

The lithology over the Maidu East fault zone provides additional evidence for the depth of colluviation on the Mehrten Formation. For example, in trench BHT–64 a coarse conglomerate occurs on the west side of the fault and fine conglomerat caps the offset sandstone unit on the east side (Figures 6 and 14). Thus, the lower half of this soil, including the "pseudopaleosol," is developed in conglomerate (and sheared sandstone) rathe than colluvium.

As mentioned previously, the thickness of the colluvial uni overlying the conglomerate in the area appears to range betwee 30 and 60 cm, based upon occurrence in the colluvium of angula fragments that are isolated from their derivative cobbles and boulders. The importance of this observation will become apparent when we discuss the orgin of the "pseudopaleosols" found in the Maidu East fault zone.

GENESIS OF CLAY WITHIN FAULT FRACTURES

The genesis of clay within fault fractures may be related to th sequence of events involving the recency of tectonic movemen along a fault system. Among the reports on the Maidu East faul zone near the Auburn damsite are two that contain contradictory hypotheses concerning the origin of clay within fault fractures. Shlemon (1977a) considers the brown clay seams within the fractures to be a result of pedogenic processes that involve translocation from soils above the fractures. O'Brient (1978) considers the brown clay to be a result of the injection of "vapor–rich juvenile ash related to pyroclastic diking and veining." In other words,Shlemon believes the clay came from above; O'Brient believes it came from below.

In this section, we test those two hypotheses, first, by examining the pink matrix, which appears characteristic of the shear zone in general, and, second, by comparing the brown clay of the fractures with the soil clay above. Then we compare the gray clay in the upper portions of some of these fractures with the clay found in the humic gley soil already discussed.

Pink Matrix

In general, the unsheared, well–cemented matrix of the conglomerate and sandstone units of the Mehrten Formation has a very pale brown color (10YR7/3d). However, extensive faulting and shearing along the Maidu East fault zone apparently has allowed penetration of meteoric water to normally inaccessible depths. Major portions of the shear zone contain a crushed–rock matrix that is mostly pink (7.5YR7/4d). An analysis of the pink

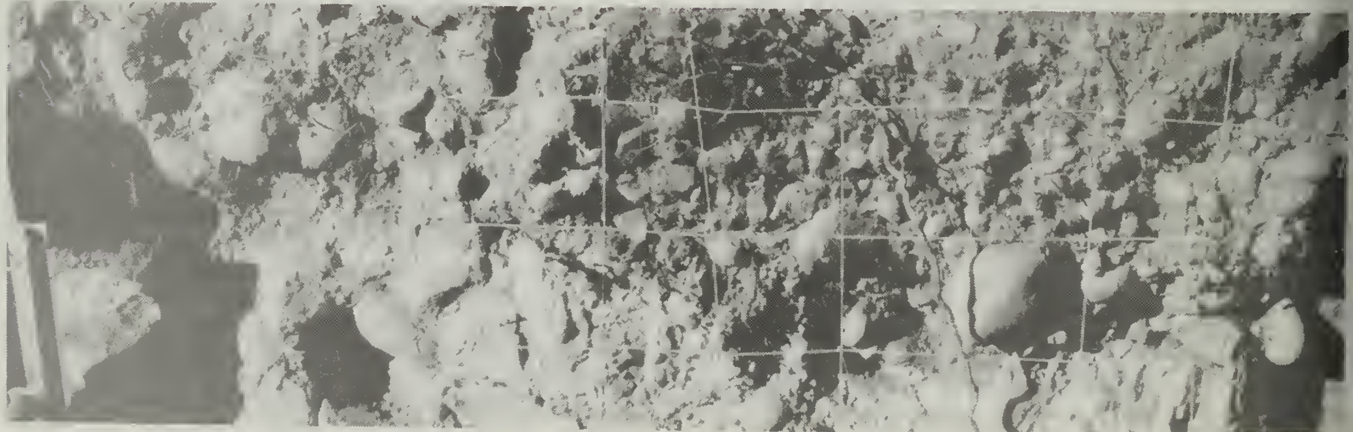

Figure 14. Lithologic change in the conglomerate overlying the "pseudopaleosol" in the Maidu East shear zone at trench BHT–64. Coarse conglomerate occurs on the west side of the fault (left) and fine conglomerate caps the offset sandstone on the east side. Squares are 30 cm wide.

atrix in trench BHT–64 showed 75 percent sand, with 13 ercent silt and 12 percent clay (Table 2, CDMG No. 291/77). his is atypical of results for the unsheared matrix of the Mehrtn Formation (Table 1, CDMG No. 319/77). Unsheared matrix amples have much lower sand/silt ratios. The sand might have een produced by crushing of gravel during the shearing. On the ther hand, the high sand contents in the sheared areas may esult from cementation of silt and clay particles by opaline ilica. The opaline silica deposition appears to be a post–shearing henomenon, perhaps related to the removal of silica from acidic oils above. This interpretation is compatible with the mineralgy of the clay fraction. The pink matrix contains only 12 perent clay, but this is primarily halloysite or extremely disordered aolinite (Table 2, CDMG No. 291/77). As mentioned, the xidized soils on the Mehrten Formation contain a similar minral. The halloysitic clay and the reddish hue of the matrix aterial is presumably a result of translocation or oxidative eathering within the sheared areas. These data tend to confirm hlemon's hypothesis of a pedogenic origin of the clay. The rown clay seams within the pink matrix are even more instrucive.

Brown Clay

Tectonic movement along the Maidu East fault has apparently roduced extensive fracturing (Frei and others, 1977, Drawing lo. 7352) in addition to shearing. Many of the former fractures re now filled with distinctive brown (7.5YR5/4md) clay (Figre 15; Shlemon, 1977a, p. 23). The brown clay (also called "red lay" in other reports) is often the first indication of the presence f the Maidu East fault zone within a trench through the Mehrtn Formation. Careful tracing of seams of brown clay frequently eads to further evidence of clear offsets of Mehrten beds (Figure 3; Schwartz and others 1977, pp. A–156 and A–157).

SHLEMON'S HYPOTHESIS

In his evaluation of the clay–filled fractures, Shlemon (1977, pp. 22–27) stated that "contemporary clay. . . is filling at least he upper part of the fractures. These clays are forming partially *in situ* and partially by translocation" (p. 27). The fractures often appear wider near the surface than at depth. In regard to he tuff–breccia in trench ST–68, Shlemon notes that "Many of he clay seams, however, do not completely penetrate the Mehrtn Formation. Most, in fact, abruptly halt at the contact between he overlying tuff–breccia" although "some clay fillings do pass irectly into the gravels giving rise to sinous coatings between lasts and matrix" (pp. 22–24). In short, Shlemon considers the rown clay a result ot pedogenesis—a soil related phenomenon.

O'BRIENT'S HYPOTHESIS

O'Brient (1978) presents a strikingly different view of the genesis of the brown clay. His hypothesis is extremely complicated and is difficult to summarize. A few major points, however, concern our discussion. First, contrary to traditional concepts, O'Brient asserts that "Mehrten strata . . . are not sedimentary deposits of volcaniclastic debris" (p. 11). Second, he considers the Mehrten to be primary pyroclastic flow of local origin. Third, instead of being a shear zone, the Maidu East fault zone consists of "tuff dikes and veins now filing . . . a complex rift or fissure system" (p. 12). Fourth, the fractures along the shear zone are "contraction features related to cooling and/or slight, differential settling of the volcanic section" (pp. 11–12). Fifth, "where filled with a distinctive red clay, they appear to have been injected by a mobile, vapor–rich juvenile ash . . . probably produced by hydrothermal argillation of the tuff–filled channels" (p. 12). In short, O'Brient considers the brown (re: "red") clay a result of volcanic extrusion and/or hydrothermal processes emanating from beneath—a phenomenon unrelated to pedogenesis.

TEST OF THE SHLEMON AND O'BRIENT HYPOTHESES

These two contradictory hypotheses are relatively easy to test from a pedogenic standpoint. Basically, the properties of the brown clay from the fractures must be compared to clay from soils developed on the Mehrten Formation[1]. To this end, a sample of brown clay was removed from a fracture at a depth of 3.5 m in trench BHT–64 along the Maidu East fault zone (Table 2, CDMG No. 324/77). This sample was finer (41 percent less than 2 um) than samples from modern soil horizons on the Mehrten Formation above (21–25 percent less than 2 um) (Table 2). This could support either hypothesis because both translocated and hydrothermally altered materials are generally finer than the soil or rock from which they are derived.

The pH of the brown clay was 7.1 while the soil above was between 4.6 and 5.5–considerably more acid. This indicates that the brown clay is not a recent accumulation, but has existed within the fracture long enough to equilibrate with the surrounding, relatively unweathered rocks of neutral pH.

The mineralogy of the brown clay supports Shlemon's hypothesis. The brown clay contains halloysite or disordered kaolinite as its only significant crystalline mineral (Tables 1 and 2; Swan and Hanson, 1977, p. C–10; O'Brient, 1978, p. 2–A). As we have seen from our study of soils on the Mehrten Formation, halloysite apparently forms under both good and poor drainage conditions, while montmorillonite forms only under poor drainage conditions. Because the brown clay is overwhelmingly dominated by halloysite and because the iron within the sample appears to be in the oxidized form, we conclude that it was once part of an oxidized soil. O'Brient's alternative hypothesis can be rejected on at least four grounds: (1) hydrothermal kaolinite is normally well–crystallized (electron micrographs showed mostly amorphous material); (2) hydrothermal solutions or intrusive dikes normally have their iron in the reduced Fe^{2+} form rather than the oxidized Fe^{3+} form which is evident from the color of the brown clay alone; (3) the contact between the brown–clay fillings and the surrounding rock is abrupt, showing little evidence of a transition between the two that usually characterizes hydrothermal alteration or weathering *in situ* (Figure 15; O'Brient, 1978, Figure IV–4 and p. 57); (4) the chemical composition of the brown clay somewhat reflects that of the glassy matrix of the Mehrten Formation, except for a drastic reduction in Ca, K, and Na (elements easily leached from soils) and an increase in Al by nearly a factor of 2 (also common in soils) (O'Brient, 1978, compare samples 1 and 4, Table C–1). Indeed, the Ca/Fe ratio of the brown clay (termed "red palagonitic groundmass" in Table C–1) decreased from 0.71 to 0.09, a result paralleling our data presented in a later section concerning chemical changes produced by soil weathering.

Shlemon's hypothesis thus appears considerably more plausible than O'Brient's. Soil clays containing oxidized iron com-

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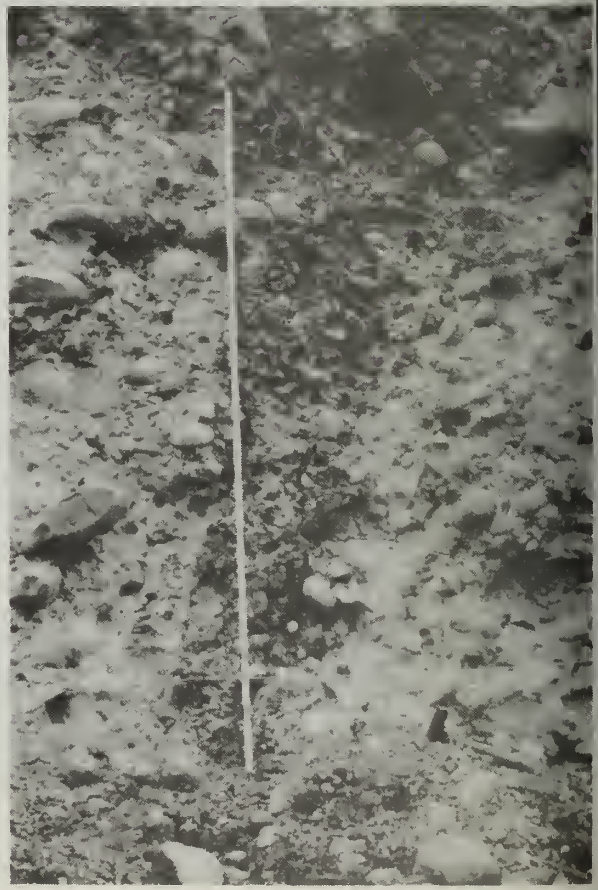
[1] O'Brient (1978) attempted such a comparison, but it was made on a single sample of weathered Mesozoic latite (pp. 57, 58, 4–A and 5–A) totally unrelated to soil formation on the volcanic Mehrten Formation.

Figure 15. Halloysitic clay possibly translocated to a depth of 5 meters in the main shear exposed in trench ST–68.

Figure 16. "Pseudopaleosol" occuring within a shear transecting trench ST–80.



ounds have been leached in suspension from upper soil horizons nd redeposited in lower soil horizons and fractures within the ehrten Formation. Some minor *in situ* alteration of the bed- ck surrounding the fractures probably accompanied the proc- ss of neutralization of the acidic soil clay as per Shlemon's esis. No doubt the porosity of the fractures was reduced fur- her by the precipitation of siliceous cements that also leached rom the acidic soils above. These processes are prevalent in early every oxidized soil, and it is not surprising that they ould also affect the bedrock beneath.

The classic work by Brewer (1964) on petrographic features n soils is especially instructive in interpreting the microstructure f the clay–filled fractures along the Maidu East fault zone. The xcellent petrographic work by O'Brient (1978) resulted in nu- erous thin sections of tectonically produced fractures lined ith "clay skins." Indeed, these clay skins look remarkably simi- ar to those in Brewer (1964, p. 205–233) which are generally ndicative of clay translocated from surface soils. For example, rewer's channel argillans (1964, p. 210 and 218) and 'Brient's Liesegang banding and tuff veins (Figures V–5, V–3, nd IV–4) are nearly identical. These remarkable similarities urther emphasize our growing awareness of the relationship between pedogenesis and tectonism. Indeed, O'Brient may be one of the first to show a tectonically–offset clay ribbon (Figure V–12B).

Gray Clay

Pedogenesis has changed along the Maidu East fault zone since deposition of the brown clay and silica cement within the fractures. The restricted drainage produced by the earlier filling of the fractures now presents a different phenomenon—the gray clay. What we choose to call"gray clay" varies according to its state of reduction and organic matter content, but typically it is a very dark grayish brown (10YR4/2m) (Figure 16). The gray clay is generally moist when first excavated and invariably associated with large modern roots that penetrate to depths well over 3.6 meters (Figure 17).

Shlemon (1977a) gives details on the probable genesis of the gray clay as part of the development of soil tongues within the Mehrten Formation. As expected, their distribution is controlled primarily by drainage conditions similar to those we found in the humic gley at BHT–66. The permeability of the bedrock must be sufficient to allow penetration by surplus water from the soils above, but water movements must not be so great that oxidation occurs. This delicate balance occurs at irregular locations along the Maidu East fault system.

The soil tongues slowly advance deeper and deeper into the fractures formerly occupied by the pink matrix and the brown clay. Consequently, the mineralogy, as well as the age, of the soil tongues varies with depth. For example, at a depth of 3.6 m the gray clay still had abundant halloysite while the montmorillonite that begins to form under these conditions was of only moderate significance (Figure 17 and Table 1, CDMG No. 270/77). At much shallower depths montmorillonite increasingly dominates —a fact to be demonstrated in a later section.

We have seen no evidence of the gray soil tongues being abandoned by roots once they have been successfully penetrated. Thus, the reduction of these segments of the shear zone and of the clay–filled fractures is not a reversible process. Likewise, the absence of significant amounts of montmorillonite indicates that both the pink matrix of the shear zone and the fractures filled with brown clay were not influenced by poor drainage for any length of time.

CLAY–FILLED FRACTURES AT SIERRA COLLEGE BOULEVARD

According to Shlemon, Begg, and Huntington (1973) and Shlemon (1977a, p. 15–27), clay–filled fractures elsewhere in the Mehrten Formation are not necessarily tectonically derived. They point out that similar clay–filled fractures occur in sub–parallel rows across the surface of a lahar unit along Sierra College Boulevard. However, the cause of these fractures is a matter of some dispute. Shlemon (1977a, p. 15) emphasizes cooling or dessication as the agent while Burnett (1963, p. 37) suggests that similar features in the Tuscan Formation north of

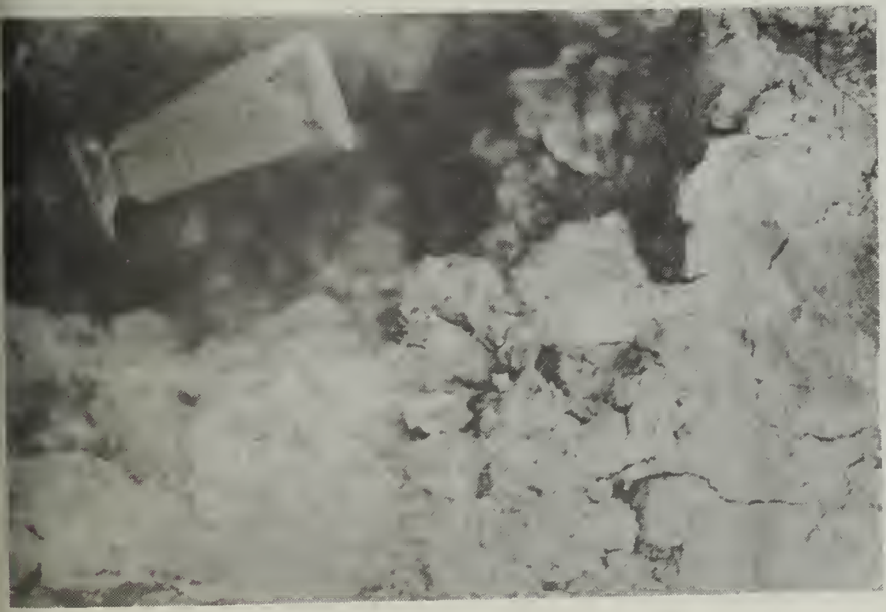


Figure 17. Root penetration into the Maidu East shear zone at a depth of 3.6 meters in ST-68 (site of sample CDMG No. 270/77).

Chico were formed by a fault–produced monocline that produced the fractures through folding (p. 39).

Recently, very small crustal movements were detected in the northern Sierra Nevada by Bennett, Taylor, and Toppozada (1977). Tentative interpretations indicate that a three centimeter drop in elevation occurred between 1947 and 1969 along a line near the proposed Auburn dam (p. 52). These movements occurred without large earthquakes and without recognized offsets on any of the faults in the region. The direction of elevation change has reversed since 1969 in the area near the Melones fault zone to the east (p. 56). Aseismic uplift and subsequent subsidence associated with major faults apparently is not an uncommon phenomenon (Bennett, 1977). Generally, shrinkage cracks due to cooling or dessication are polygonal rather than parallel. The parallel fractures at Sierra College Boulevard are probably a result of minor crustal movements associated with the regional tectonics.

Back at the Auburn damsite, the evidence at trench ST–68 indicates clearly that minor monoclinal fractures of this type are associated with a lahar (Tb) that was displaced along the Maidu East fault (Frei and others, 1977, Drawing no. 7352). In this case, the offset lahar also has a convex appearance on the west side of the main shear conforming to the vertical component of movement. Thus, it is likely that the fractures at Sierra College Boulevard and at Auburn damsite both have a tectonic origin.

In any case, we sampled the clay–filled fractures at Sierra College Boulevard in order to compare the genesis of the clay with that at Auburn damsite. The material was a light brownish gray (2.5Y6/2m), indicating that it formed under poor drainage conditions. The clay fraction of a sample of this material had abundant quantities of both halloysite and montmorillonite (Table 1, CDMG No. 306/77). The pH was 5.92. These are properties nearly identical to those of the gray clay and of humic gley soil at the Auburn damsite. Thus, the genesis of these clays appears similar. The clay content of the fractures is about 85 percent compared to 30–49 percent in the humic gley horizons near the proposed Auburn dam. Consequently, the sand and silt contents are low, also indicating either a great degree of weathering or deposition through translocation from above. Because both halloysite and montmorillonite are present, we can not ru out either possibility.

However, the presence of montmorillonite indicates that po drainage conditions have prevailed in these fractures for a lon time. The gleyed color indicates that such conditions still exi today. The significance of these reduced clays will become appa ent when we attempt to explain the unique fault features els where in the Mehrten Formation.

ORIGIN OF "PSEUDOPALEOSOLS"

A paleosol is a fossil soil. We have introduced the term "pseudopaleosol" for a soil feature that may be mistaken for paleosol. A paleosol represents a period of landscape stabilit which has been followed by one or more periods of relativ landscape instability. Features that show only evidence of con temporary soil formation should not be considered paleosols.

Such features are common in the Maidu East fault zone wher ever it cuts the Mehrten Formation (Figures 3, 14, 16, and 18) These irregular clay bodies are invariably linked to the modern drainage of, or accumulation of water along, shears or geologi contacts. The features have been described correctly as soi tongues or IIIB22g horizons, (Shlemon, 1977a). Where soi tongues form laterally along geologic contacts, they often tak on many of the characteristics of buried soils (Schwartz and others, 1977, pp. 72, 73, and 132). However, as Shlemon (1977b p. 12–14) points out, these features cannot be considered paleo sols in the usual sense of the term. Certainly they have not been at the surface, undergoing the effects of pedoturbation, etc., tha normally characterize a soil. The "pseudopaleosol" in trench GT–1 (Figure 1) is an excellent example (Borchardt, Rice, and Taylor, 1978, Figure 11). In this trench, a laterally extended pseudopaleosol is overlain by undisturbed and relatively unweathered conglomerate that is millions of years older than the pseudopaleosol.

Unfortunately, the concept of the pseudopaleosol is not without difficulties. It is clear from the previous study of the gray clay within the fault fractures that pseudopaleosols, as well as soil tongues in general, are surface–related features. They might well

Figure 18. The main fault feature in trench BHT –53 consisting of colluvium overlying weathered conglomerate and a "pseudopaleosol" that is developing contemporaneously in an old shear zone.

present a period of landscape stability equivalent to that ypothesized for the Foothills paleosol (Borchardt, Rice, and aylor, 1980). In that event, the pseudopaleosols and soil ngues have been slowly developing deeper and deeper into e Mehrten Formation during the last 130,000 years. Thus, e upper portions of these features are the oldest, widest, and st developed (Figures 3, 16 and 18; Borchardt, Rice, and aylor, 1980, Figures 10 and 11). In the following section, we esent a detailed study of a fault feature involving most of the ncepts discussed in the preceeding sections.

SOIL DEVELOPMENT AND TECTONISM AT TRENCH BHT–53

The striking fault feature at trench BHT–53 (Figures 3 and 3) has been cause for much concern about the recency of dis-acement along the Maidu East fault zone. First, the U.S. Geo-gical Survey issued a preliminary memorandum saying that ate Quaternary offset is clearly shown" in this trench because a buried colluvial unit and its contact with the underlying ertiary conglomerate is sheared and displaced a minimum of 30 m across a graben–like structure" (U.S. Geological Survey, 977, p. 1 and Figure 1). Next, Shlemon (1977a, p. 2) took issue ith this interpretation, saying that "colluvial and soil–filled epressions above 'shear' zones in the Mehrten Formation are oil tongues . . . forming *in situ* rather than displaced downward y post–colluvial faulting." Indeed, soil features immediately bove the major shear in the trench appear thicker on the east ide than on the west side (Figures 3 and 18). The orientation f cobbles and boulders gives the appearance of their gravitation-l movement within a fissure produced by faulting. Additionally, n accumulation of grayish brown clay within the shear zone ives the appearance of freshly produced gouge.

Trench BHT–53 is only 800 m from the right abutment of the roposed Auburn dam. This fact, along with the controversial ature of the above interpretations, indicates that this unusual oil feature warranted further detailed study.

Evaluation of Vertical and Lateral Homogeneity of Soil in Trench BHT–53

Soil properties and soil development vary with depth. This ariation often can be used to evaluate the uniformity of the riginal geologic material from which the soil formed (Bor-hardt, Hole, and Jackson, 1968; Borchardt and Theisen, 1971). Likewise, the progress of chemical leaching and weathering can e followed as a function of depth (Borchardt and Harward, 1971; Borchardt, Harward, and Knox, 1971).

SAMPLING

For the study of trench BHT–53, we sampled three soil profiles. Profile A was sampled 1.5 m to the east of the main shear. Profile B was sampled directly above the shear, and profile C was sampled 1.5 m west of the shear (Figures 3 and 18). Samples were taken at about 5 to 10 cm intervals from the surface to a point slightly below the base of the B horizon. The single exception was profile B where we encountered a "pseudopaleosol" or "soil tongue" at depths greater than one meter. Only very small samples were obtained from this point down to a depth of 180 cm. These were placed in storage in the event that further studies justify their use. In the meantime, sample CDMG No. 192/77 was considered representative of the remainder of profile B (Figure 3). As mentioned previously, "pseudopaleosol" development is tremendously irregular. A thorough study of one of these features would require a detailed 3–dimensional sampling plan. Recent deepening of this trench shows that this one extends for a least two more meters.

Certain items can be pointed out concerning the log of the main shear in BHT–53 (Figure 3). First, Mehrten sandstone (Ts) has been offset against Mehrten conglomerate (Tg). According to data from ST–68, the offset here is nearly 5 m down to the east. Second, the sandstone is capped by a thin veneer of unweathered conglomerate. Third, the soil–bedrock boundary is very irregular. This is particularly noticeable in the area of the main shear. Fourth, an area of mottling exists within the shear at a depth greater than the normal soil depth (130 cm). Fifth, saprolites (rocks weathered in place and so fragile that they would not survive any significant transport) do not occur at depths shallower than 55 cm. Sixth, the upper 30 cm of soil has fewer cobbles than the subsoil.

In order to determine the uniformity of this soil, we determined and graphed various properties, pH (Figure 19), Ca/Fe ratios (Figure 20), coarse sand and clay contents (Figure 2), coarse sand to fine sand ratios (Figure 12), and silt contents (Figure 21). Possibly, such depth functions might reveal otherwise "hidden" stratigraphy that could indicate whether or not the fault moved recently along this shear. In any case, we expect to learn more about the genesis and relative age of this soil by evaluating such data.

pH

The pH of a soil often reveals its age. Young soils have pH values similar to those of the parent material (the initial geologic material from which the soil weathered). Most geologic materials have a pH near neutrality. The Mehrten Formation appears to be no exception, with the pH being about 6 (Figures 19a and 19c). The pH depth function for profile B in Figure 19b is rather typical for soils. The pH usually decreases with nearness to the surface until it reaches a minimum, in this case, at the 18 cm depth where the pH is 4.4. From this point, the pH increases with nearness to the surface as a result of the recycling of basic elements (such as calcium) through decay of leaf litter from deciduous trees (oak in this case).

A comparison of profiles A, B, and C shows pH minimums at 13, 18, and 26 cm, respectively (Figure 19). Further local variability is indicated by the depth at which a pH of 5.5 is encountered. If we ignore the upper horizons that contain decaying leaf litter, we find this depth occurs at 35, 95, and 67 cm for profiles A, B, and C, respectively. By this measure, the depth of intense soil weathering is greater immediately above the shear than it is on the west side of the fault. Likewise, the west side has a greater volume of acid soil than the east side of the fault. Possibly, this indicates that rainwater laden with carbonic and humic acids moves laterally (Huggett, 1976) downslope from profile C on the west and then tends to move vertically through the sheared zone beneath profile B (Figure 3). Profile B, therefore, gets more than its share of moisture while profile C gets slightly less than its share. By this reasoning, profile A, to the east, gets much less moisture than either profile B or C. This may account for the youthful appearance of the pH depth function for profile A (Figure 19a).

Ca/Fe RATIOS

Ca/Fe ratios were determined on the less than 420 um material in order to evaluate the leaching of Ca from feldspars in

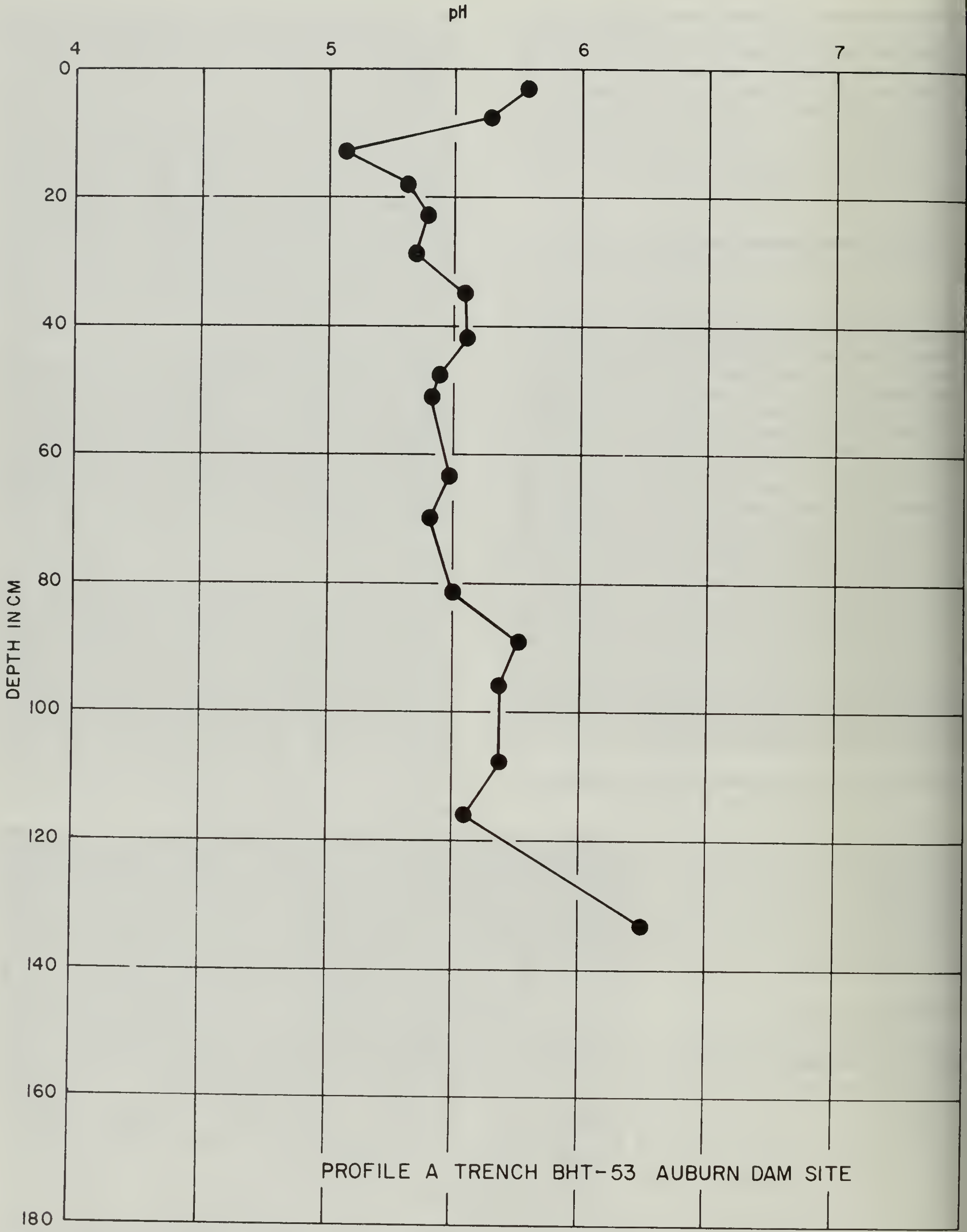


Figure 19a. Depth function for pH in profile A.

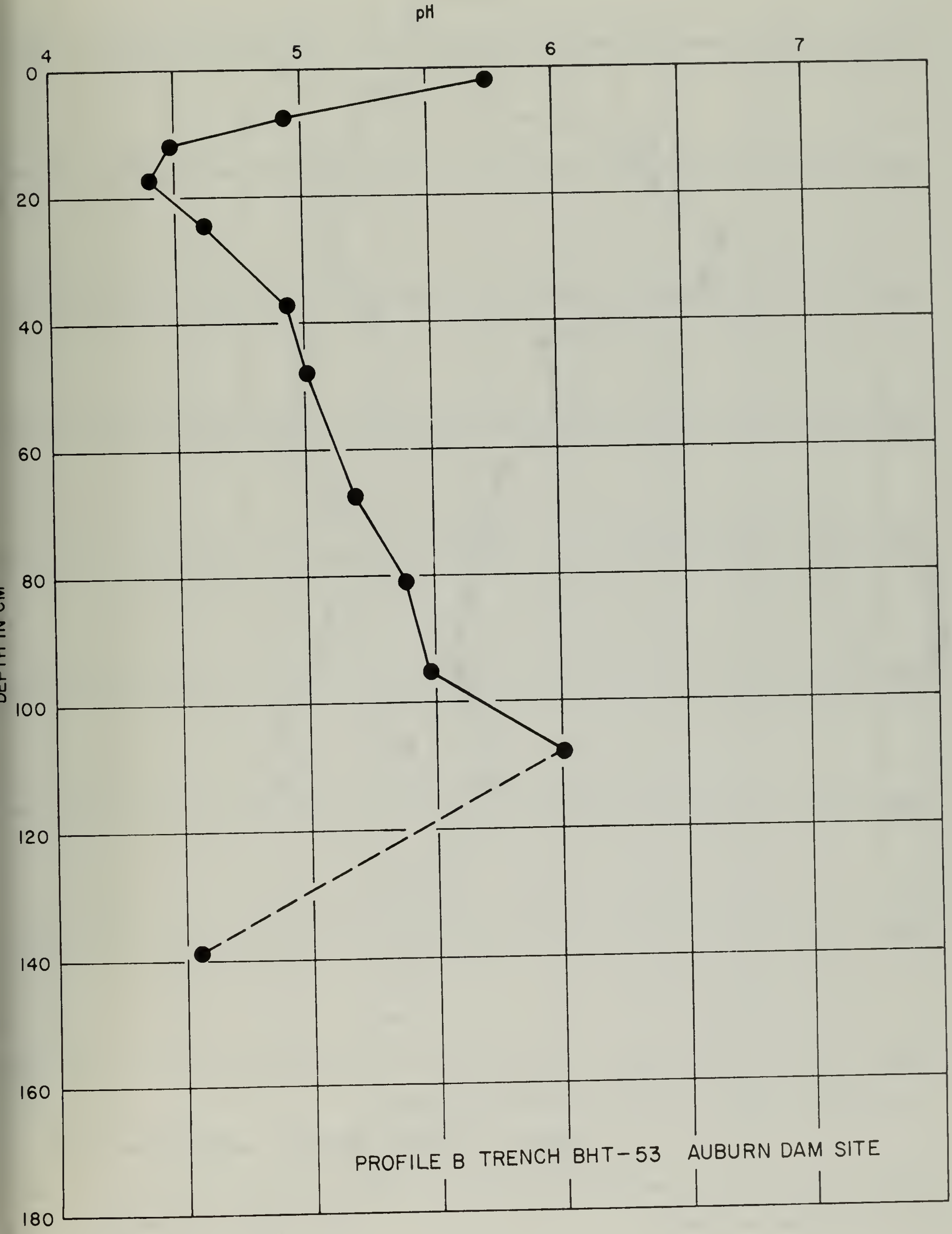


Figure 19b. Depth function for pH in profile B.

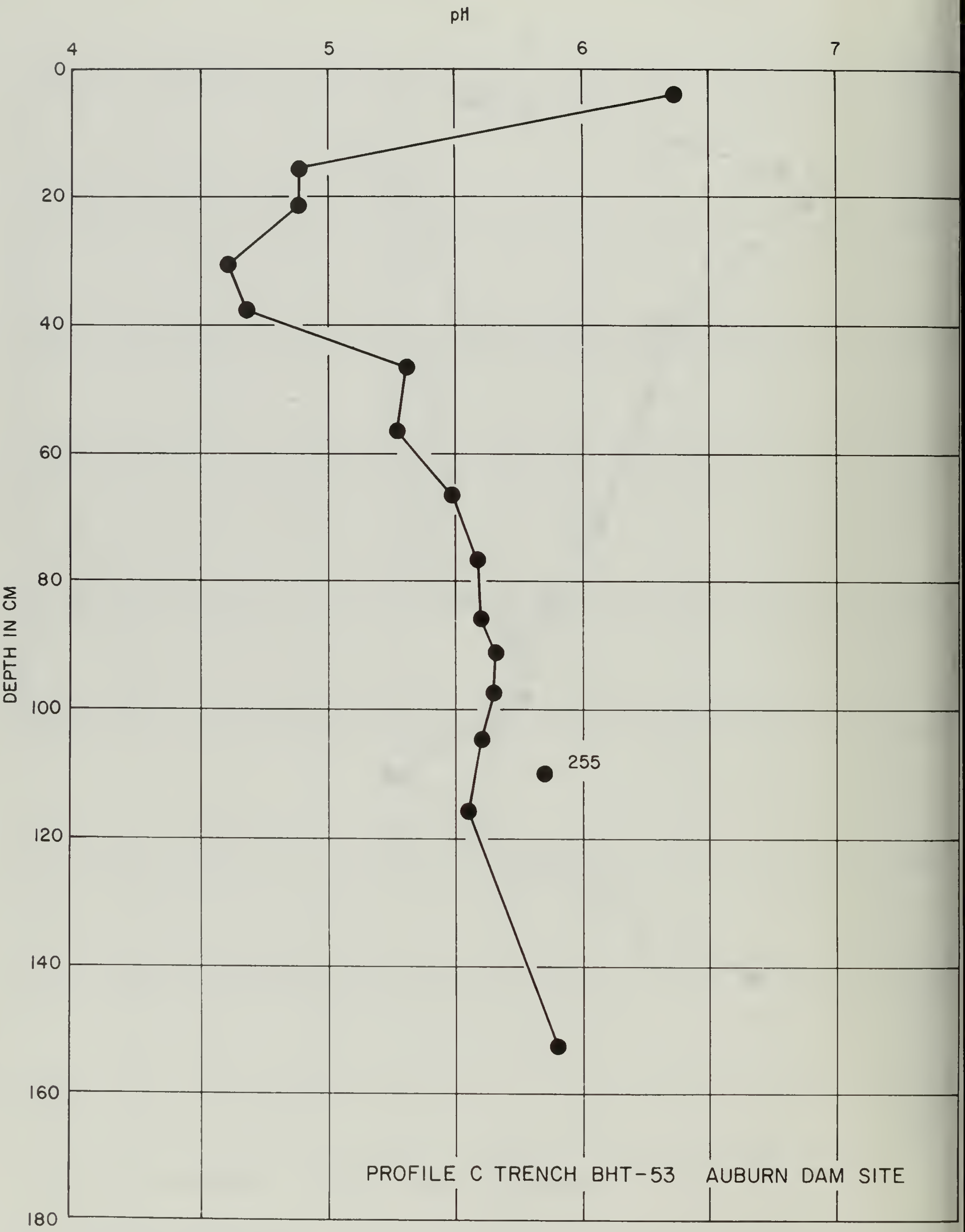
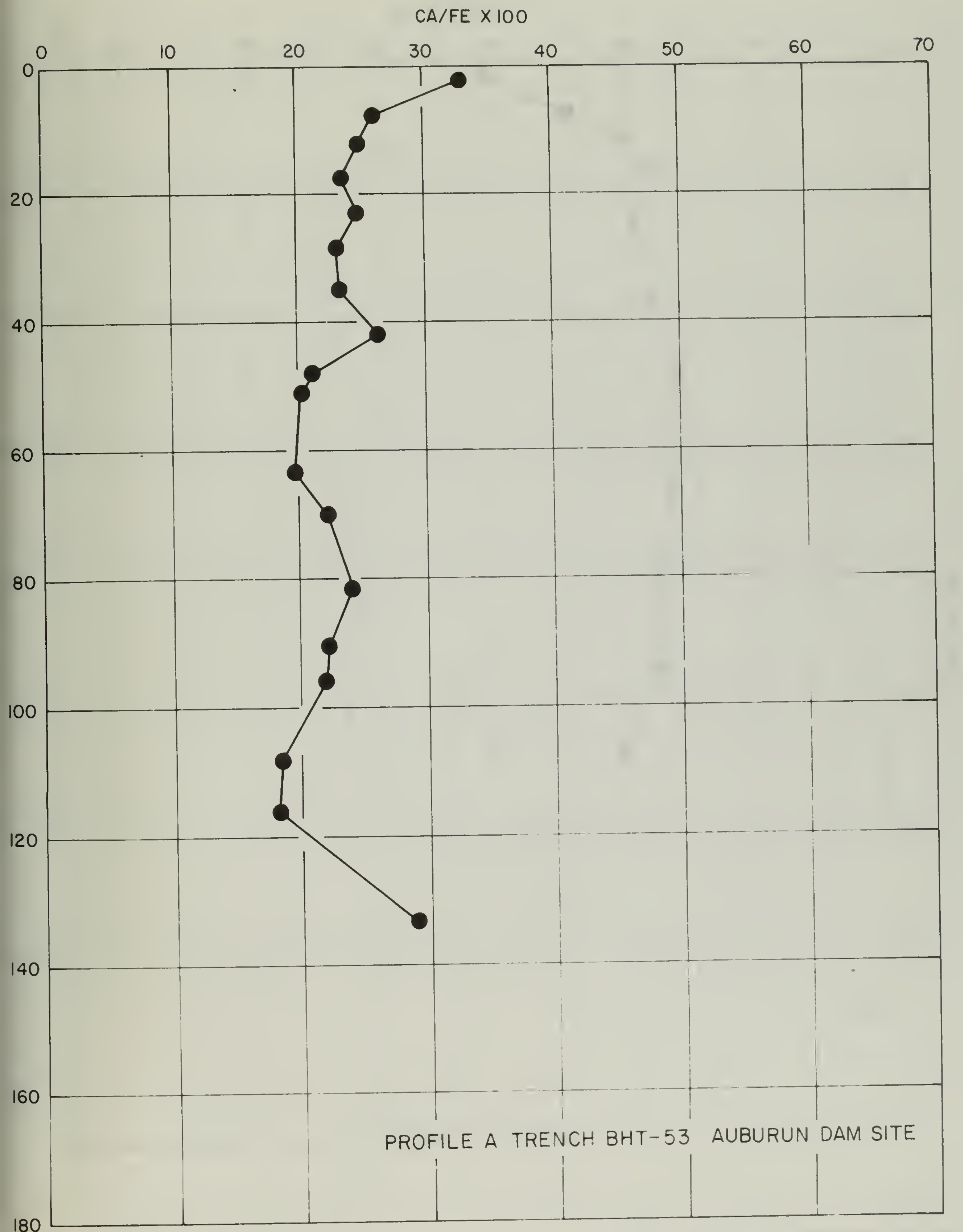


Figure 19c. Depth function for pH in profile C.



igure 20a. Depth function for Ca/Fe ratios in profile A.

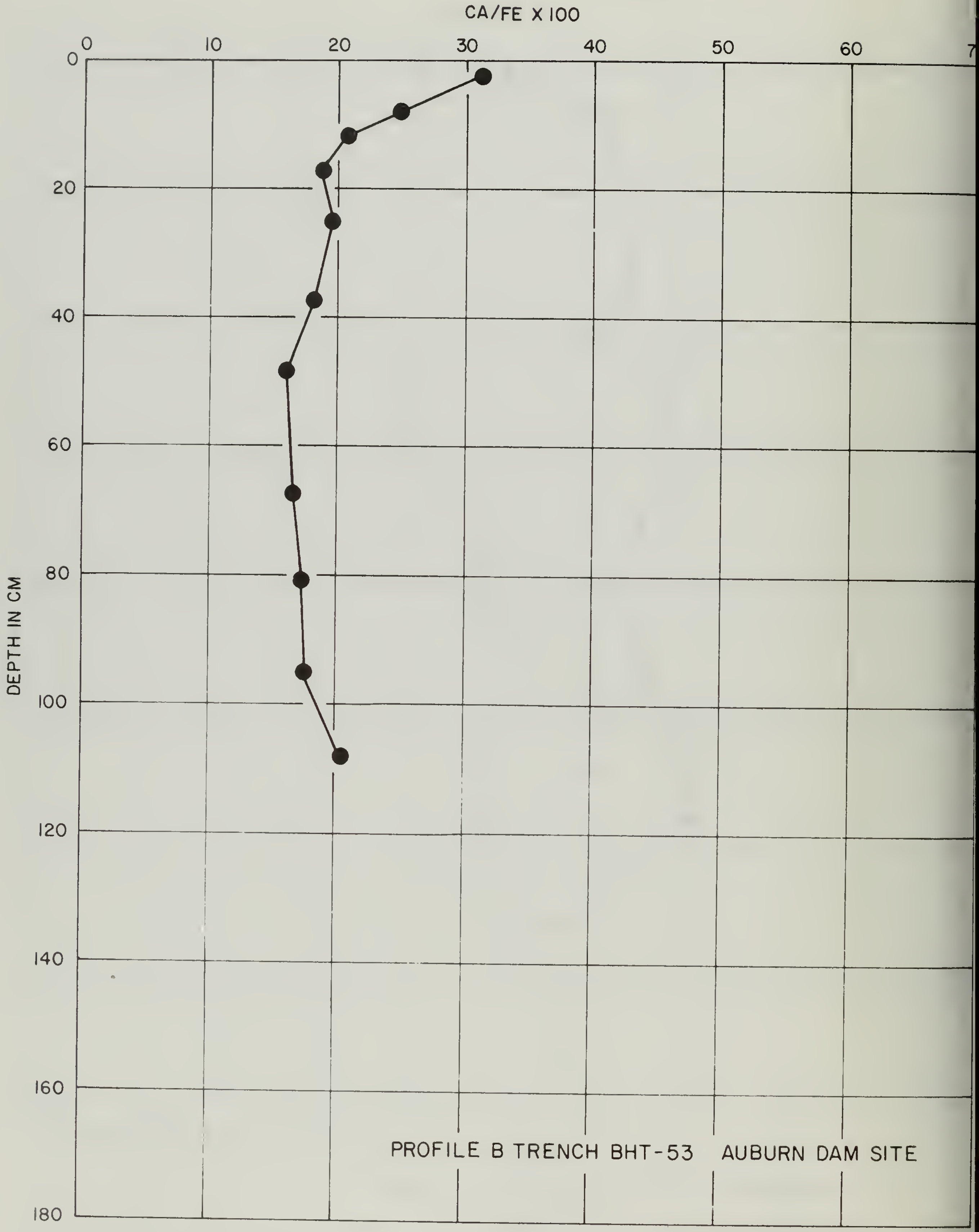


Figure 20b. Depth function for Co/Fe rotios in profile B.

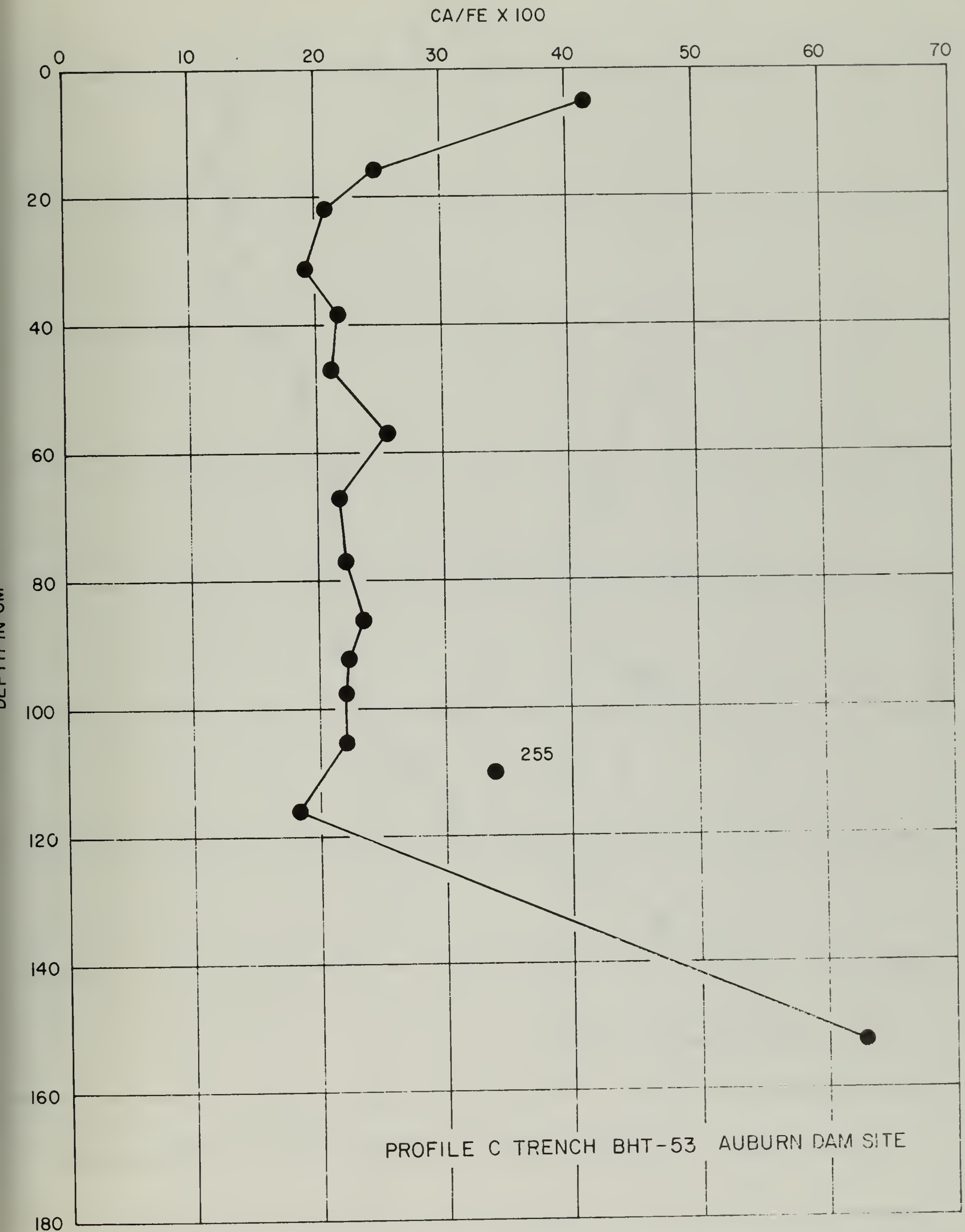


Figure 20c. Depth function for Ca/Fe rotios in profile C .

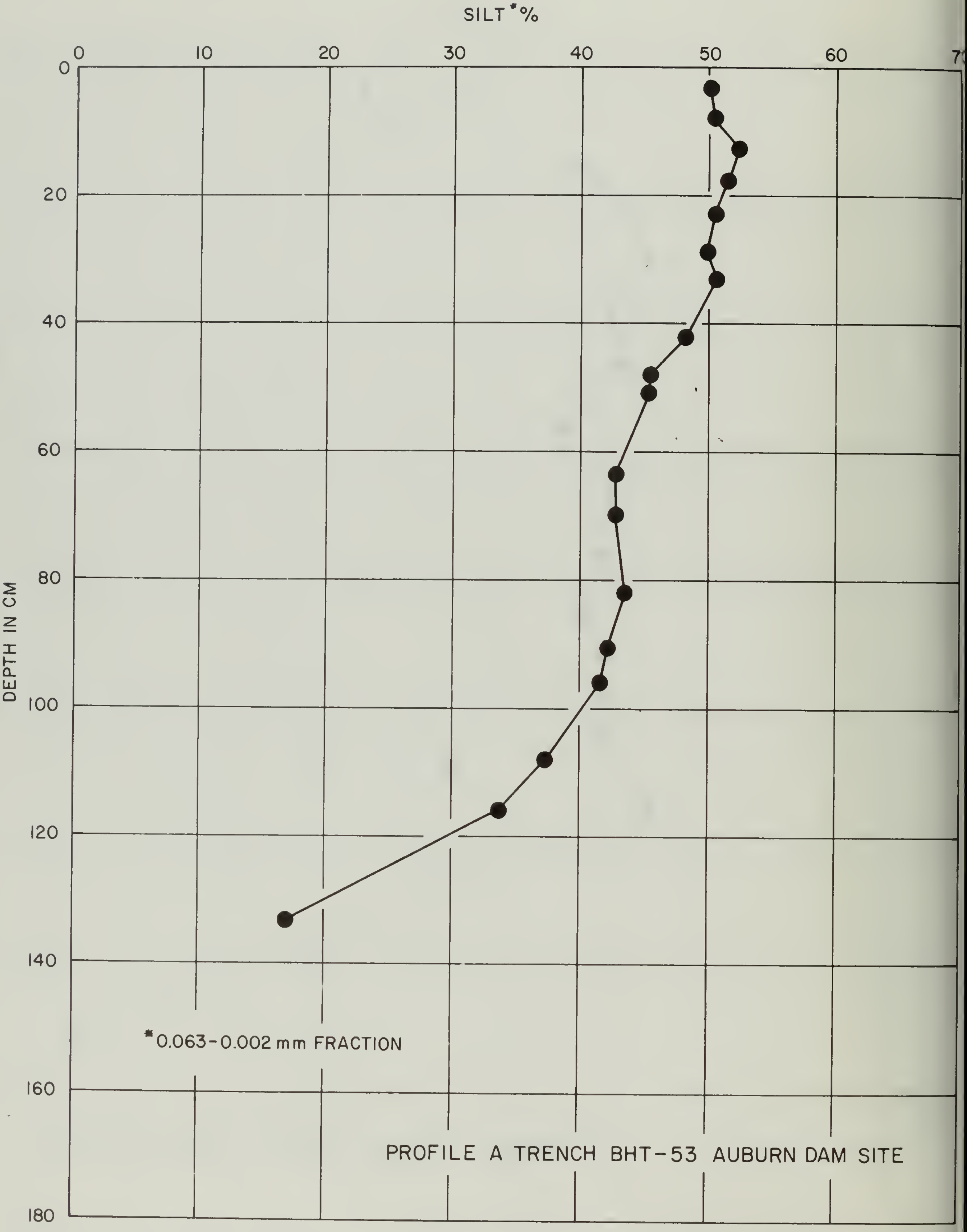


Figure 21a. Depth function for silt contents in profile A.

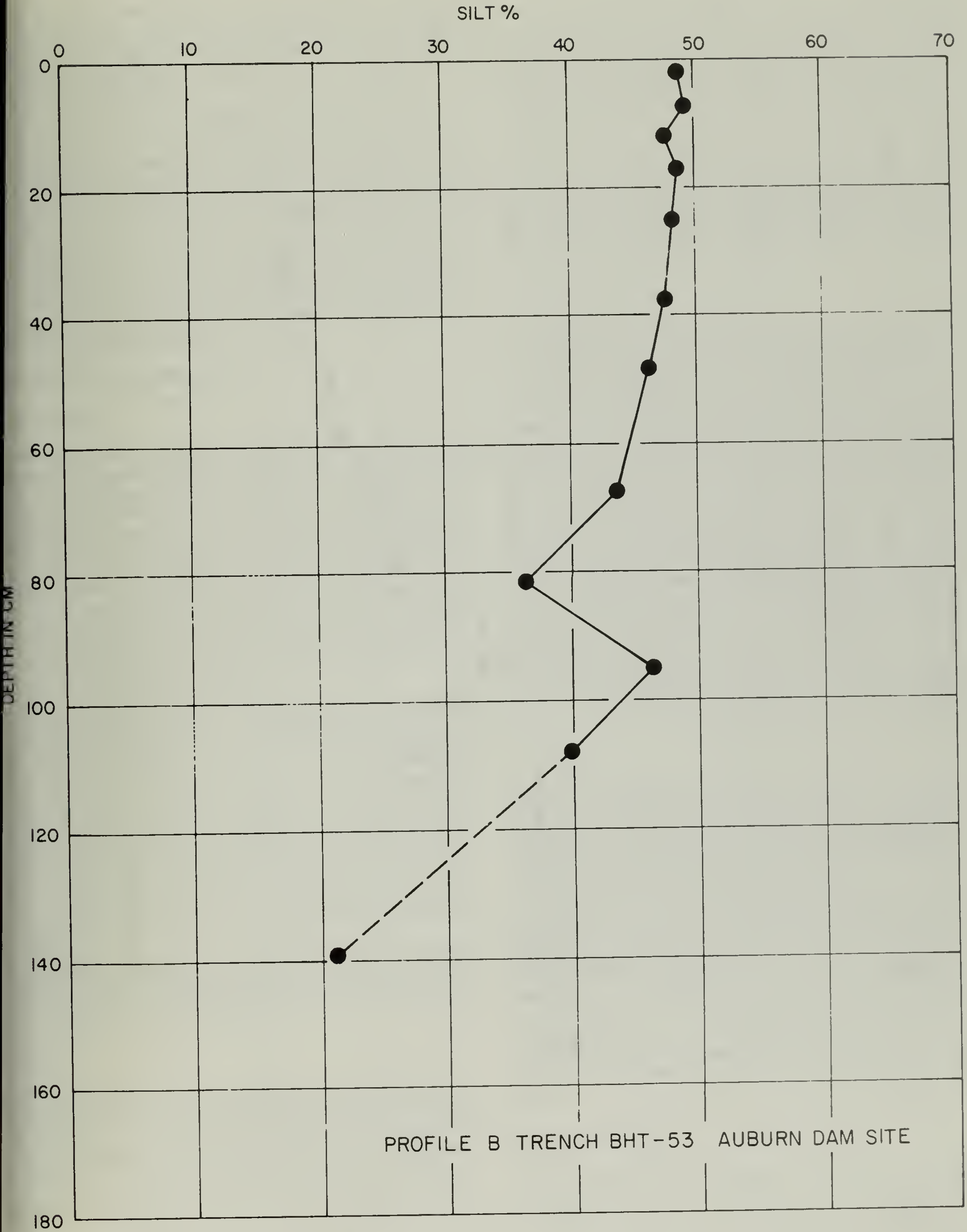


Figure 21b. Depth function for silt contents in profile B.

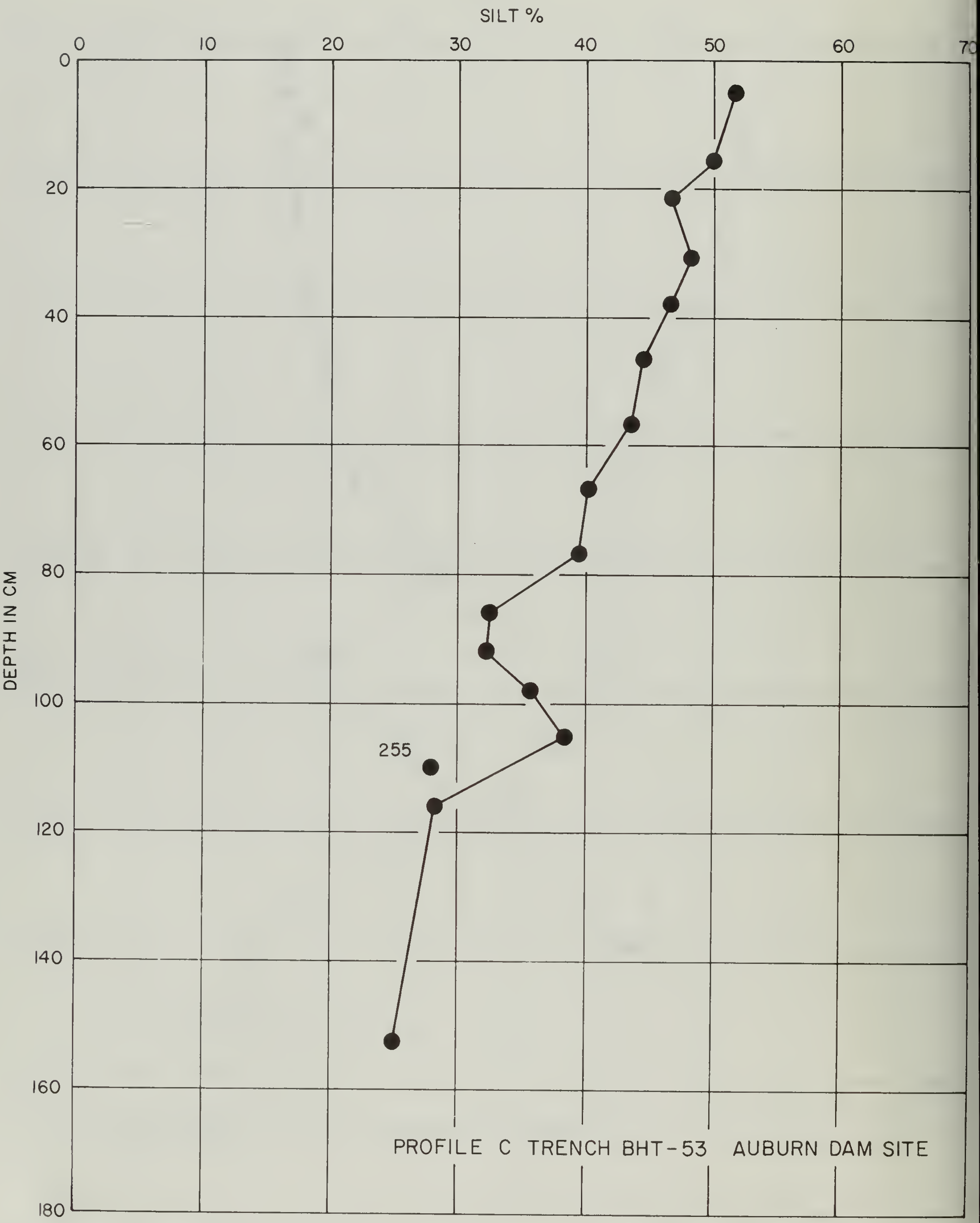


Figure 21c. Depth function for silt contents in profile C .

elation to the accumulation of iron oxides within the soil (Borhardt and Theisen, 1971). The conglomeratic matrix had the ighest Ca/Fe ratio, 0.64 (Figure 20c). The lowest Ca/Fe ratio vas 0.16 which occurred at a depth of 48 cm in profile B above he shear (Figure 20b).

For the most part, the depth functions for profiles A, B, and C are relatively uniform (Figure 20). The increase in Ca/Fe atio within 20 cm of the surface is apparently a result of the ncrease in exchangeable calcium that was also reflected in the lepth functions for pH (Figure 19). The irregular soil–bedrock boundary in profile C was reflected in a higher Ca/Fe ratio for ample 255/77 at 110 cm than for sample 256/77 at 116 cm. This ubstantiates the field evidence indicating sample 255/77 was ess oxidized and less weathered than sample 256/77, and shows hat the colluvium–residuum boundary is not coincident with he soil–bedrock boundary. So far, neither pH nor Ca/Fe ratios ndicate a clear change in composition that might indicate the olluvium–residuum boundary.

PARTICLE SIZE DISTRIBUTION

Coarse sand

Evidence for two different lithologies is obtained easiest through an analysis of particle size (Borchardt, Hole, and Jackson, 1968). Changes in the content of any one size fraction may indicate the effects of either weathering or mixing of geologic materials. For example, the parent material (tuffaceous sandstone) in profile A had 44 percent coarse sand (2.0–0.6 mm)[1] at the 133 cm depth (CDMG No. 236/77, Figure 2a). This declined through physical and chemical breakdown to 15 percent in the lower part of the B horizon at 116 cm and thence to 6 percent at 50 cm. Between the 50 cm depth and the surface, the content of coarse sand remains constant at about 6 percent. The 55 cm depth corresponds to the saprolite boundary noted on the log of this trench (Figure 3).

Wherever saprolitic rocks occur, the physical disturbance of the soil has been minimal for a period of time. For diabase in dolomitic till in Wisconsin, this period of time is less than since the last glacial advance about 12,800 years ago (Borchardt, Hole, Jackson, 1968, Table 3). Because these saprolitic andesite cobbles do not occur at depths shallower than 55 cm, we consider this the active zone of pedoturbation. Any modern colluviation would certainly take place within this depth. We suggest that this is also the maximum limit for colluviation within the feature. As mentioned previously, the maximum extent of colluvial deposition in the area is limited to 100 cm as measured on a 14–degree slope in more easily eroded sandstone (Figures 4 and 5).

The coarse sand contents of profiles B and C are generally uniform with depth (Figures 2b and 2c). Once again, the irregularity of the soil–bedrock boundary in profile C is indicated between 80 and 120 cm (Figure 2c).

Clay

The clay contents of a soil normally increase with depth to a maximum within the "B" or "argillic" horizon, and then decline to values found in the parent material (Figure 2a). Depth functions for clay contents in profiles A, B, and C are characterized by increases in clay from 15 percent in the surface to 25, 30, and 29 percent in B horizons, respectively (Figure 2). The parent material had only 6–9 percent clay (profiles A and C). Thus, soils of the Mehrten Formation have up to a five–fold increase in clay as a result of soil formation. Normally, soils with this much clay formation followed by clay translocation, have a well–developed "clay bulge." This would be a smooth transition to a maximum accumulation of clay in the B horizon followed by a smooth transition to the minimum in the parent material.

Clay translocation is indicated in these soils by clay films in soil pores and on ped faces in the B horizon (Shlemon, 1977a, p. 34). Thus, we have considerable clay formation and significant clay translocation indicating the effects of pre–Holocene soil development. On the other hand, the absence of a well–developed clay bulge and the vertical uniformity of upper horizons may represent the effects of local colluviation, perhaps of early Holocene age (Borchardt, Rice, and Taylor, 1978).

Coarse sand/fine sand ratios

Sometimes additional information can be gained by plotting depth functions for ratios instead of contents for a single fraction. Coarse sand (2.0–0.6 mm) and fine sand (0.150–0.075 mm) are two fractions that are normally not subject to illuviation. The ratios of these two fractions should be relatively constant for the more stable minerals in soils. This is not the case for the soils developed on the Mehrten Formation. For example, there is five or six times as much coarse sand in the parent material as there is fine sand (Figures 12a and 12c). The soil horizons, however, have about equal proportions of coarse and fine sand. This illustrates primarily the physical and chemical breakdown of the volcanic glass that constitutes much of the matrix material of the Mehrten Formation. Soil weathering appears to reduce this ratio to less than 1.0 where it remains relatively constant at depths above the saprolite boundary (Figures 12 and 3). In profile A, the ratio increases gradually between 60 and 130 cm (Figure 12a). In profile B, it increases gradually between 40 and 110 cm (Figure 12b). In profile C, it varies erratically at depths between 80 and 120 cm, (Figure 12c), once again indicating an irregular soil–bedrock boundary.

Silt

Silt contents in these three profiles tend to decrease with depth (Figure 21). Presumably, the silt–size minerals are released from the glassy matrix of sand and gravel particles during soil weathering. There was only 17 to 25 percent silt in the parent material, but the silt content gradually increased to 50 percent near the surface as a result of soil weathering (Figure 21).

In general, these soils weather through the accumulation of silt and clay at the expense of coarser fractions (Figure 22). The particles in weathered horizons are well distributed throughout all size ranges. In fact, a log linear distribution, as shown for sample 257/77, is typical of all soil horizons developed on the Mehrten Formation. There doesn't appear to be any bimodality in particle size or drastic changes in soil properties that would be inconsistent with soil development exclusively from the Mehrten Formation. Likewise, these data are consistent with small amounts of local colluviation, but only for depths less than 55 cm.

CLAY MINERALOGY

The well–drained, oxidized soils on the Mehrten Formation contain essentially one clay mineral, halloysite. Halloysite and

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[1] Please note that this definition of coarse sand is slightly, though insignificantly, different from the one in Tables 1 and 2 (2.0–1.0 mm). Other particle size definitions vary slightly in this section as well.

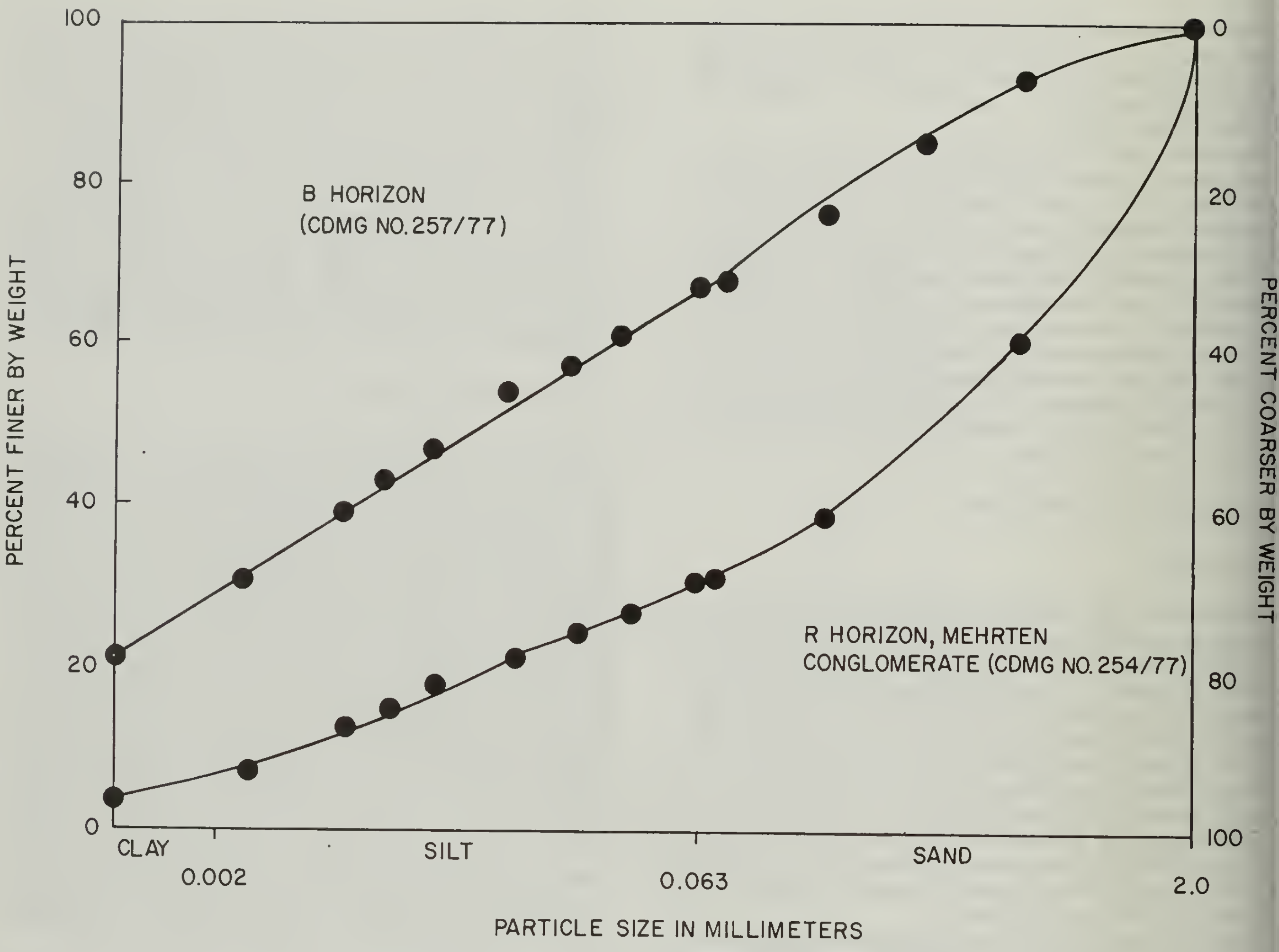

Figure 22. Particle size distribution curves showing the effects of weathering on Mehrten conglomerate in profile C.

then kaolinite is a common result of soil formation in pyroclastic deposits (Millot, 1970, p. 47; Figure 23). The identification of this mineral as halloysite instead of kaolinite is based upon the low–angle x–ray scattering of the 7.2A peak and its occurrence in samples formed under poor drainage. The 7.2A peak increases in size when field moist samples are air dried (Figure 23). Apparently, this air drying step helps to orient the particles. This generally would not be a problem with well–crystallized kaolinite. On the other hand, the mineral is not a well organized hydrated halloysite for it did not display a 10A hydrated peak prior to air drying. The mineral is accompanied by a large amount of non–crystalline material, making identification difficult. The samples could very well contain both halloysite and disordered kaolinite.

The relative intensity of the x–ray peak of the halloysite in the clay fraction is very unifiorm throughout the oxidized soil profiles developed on the Mehrten Formation (Figure 24). The x–ray patterns for A1, B2, and B3 horizons are nearly identical. There is slightly more low–angle broadening of the 7.2A peak from the R horizon, indicating its less well–crystallized state (Figure 24). Also, the R horizon had one–third to one–half as much clay as the more weathered A and B horizons (Figure 2a).

Unlike these oxidized horizons, the reduced, gleyed portions of this soil contain significant quantities of a poorly crystallized montmorillonite (Figures 25 and 3). As previously mentioned, these grayish brown soil tongues, or "pseudopaleosols," occur wherever ground water penetrates and is perched within the Mehrten Formation. This is primarily wherever the formation has been sheared or broken by fault movement (Figures 3, 14, 16, 17 and 18). A sample of the gray clay in the main shear in trench ST–68 had montmorillonite at a depth of 3.6 meters (Figure 17). The characteristics of this clay (Figure 10) are remarkably similar to those of the gleyed soil formed in a spring area in trench BHT–66 (Figure 9). We conclude that this montmorillonite has a common origin in a perched water table where silica potentials are high enough for its formation (Borchardt, 1977a).

The presence of halloysite in these gleyed portions would support either of two hypotheses: (1) that the halloysite was formed in a well–drained soil at low pH (about 5) and then translocated to depths below the present water table, or (2) that the halloysite also formed under conditions of poor drainage. As we saw in the discussion of the brown clay and of trench BHT–66, there is support for both hypotheses.

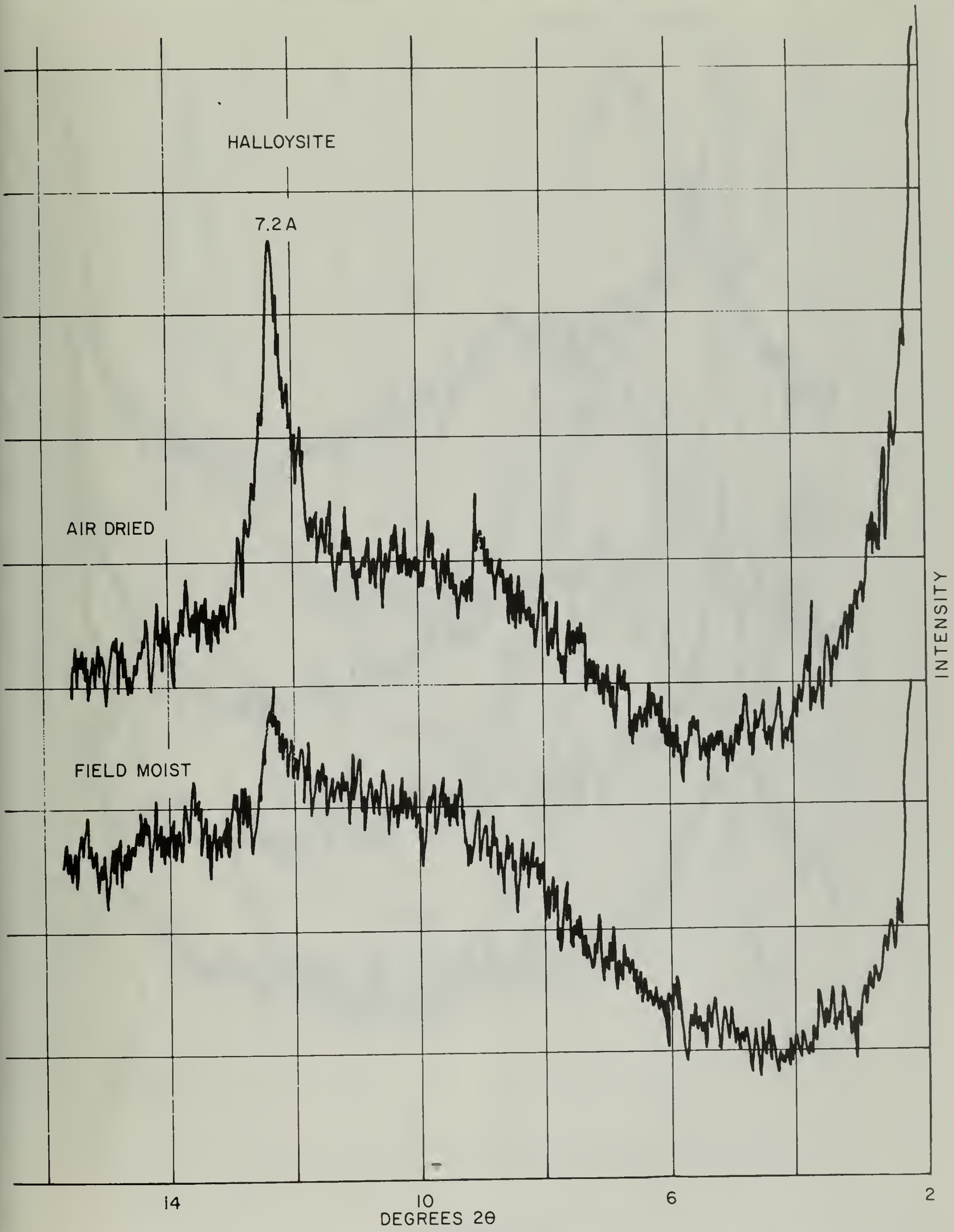

Figure 23. X–ray diffraction patterns showing the effect of air drying on halloysite from soils of the Mehrten Formation (CDMG 314/77). A well–crystallized kaolinite would have a 7A peak regardless of moisture conditions.

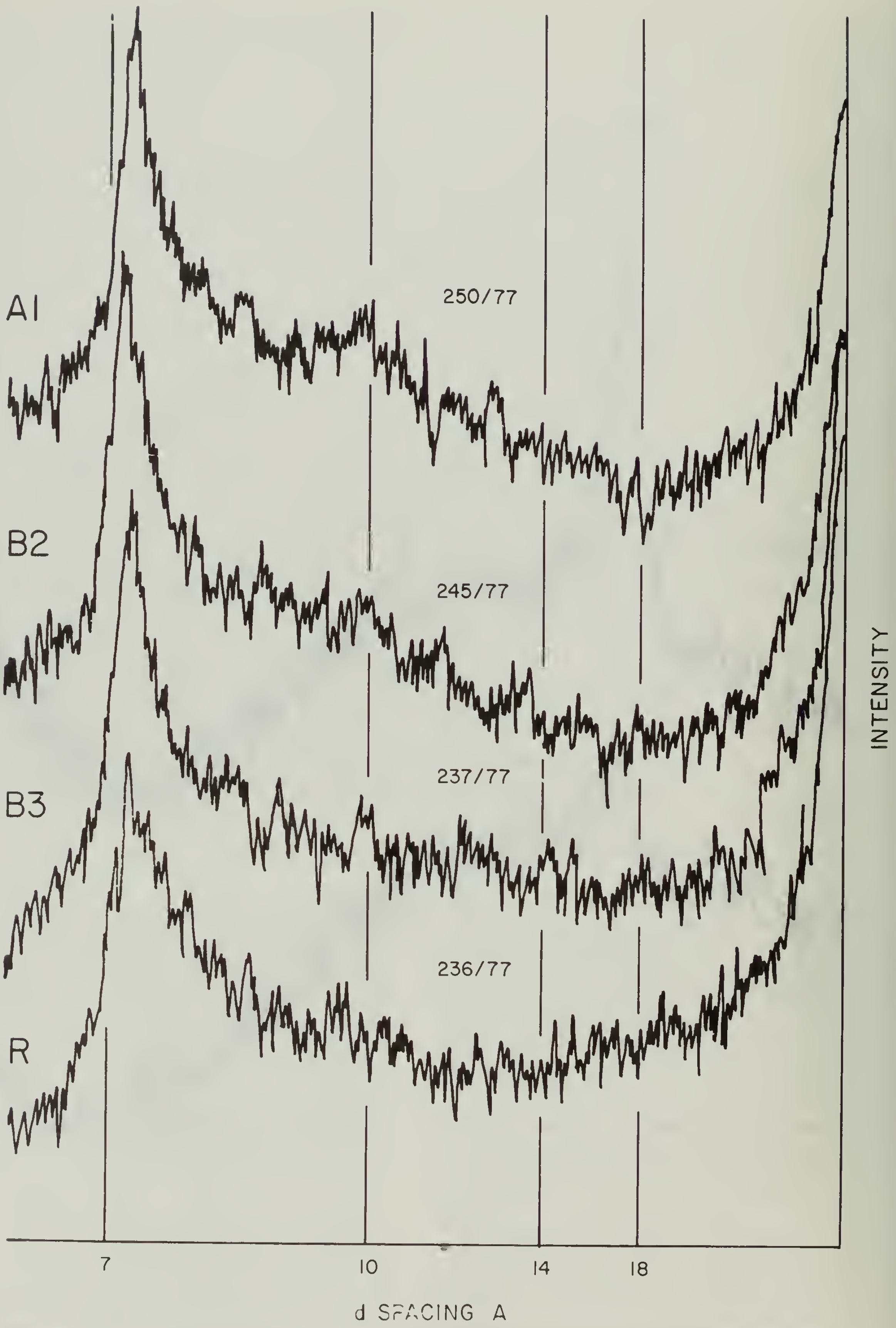

Figure 24. X–ray diffraction patterns of profile A showing the homogeneity of halloysite in clays formed from the Mehrten Formation in trench BHT–53 (Mg saturated, 54 percent relative humidity).

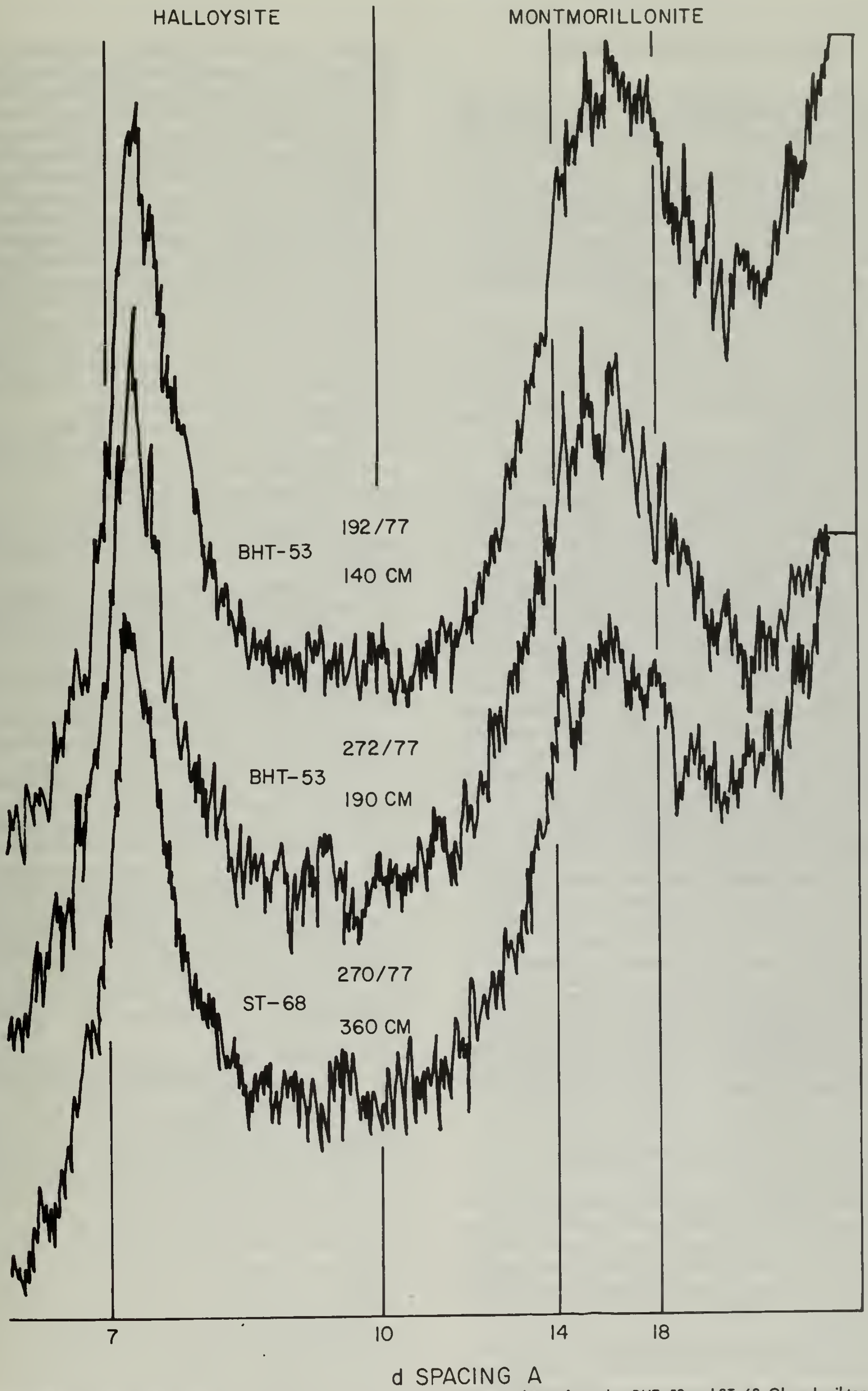

Figure 25. X–ray diffraction patterns of the grayish brawn clay in the main shear of trenches BHT–53 and ST–68. Gleyed soil tongues cantain mantmarillanite as well as halloysite to depths over three meters (Mg saturated, 54 percent relative humidity).

Significance for Age of Faulting

Detailed analyses of three profiles to the left of, right of, and above the main fault feature in trench BHT–53 did not substantiate early speculations concerning an offset colluvial unit. The initially striking appearance of this feature involves a host of factors, including (1) pseudopaleosol formation under poor drainage conditions within a perched water table, (2) halloysitic soil formation under oxidizing conditions within Mehrten conglomerate, (3) colluvial deposition (early Holocene) limited to the 55–cm depth and not coincident with the soil/bedrock boundary, and (4) pseudopaleosol degradation as a result of decreased precipitation during the Holocene.

It is possible that some of the apparent orientation of cobbles in the feature (Figure 18) is related to pseudopaleosol formation and/or degradation as suggested by Shlemon (1977a, p. 15). Such apparent orientation was not evident in nearby exposures in which the pseudopaleosol was less developed (see, for example, Figures 14 and 16).

Significantly, undisturbed saprolitic cobbles overlain by "angular orphans" mark the boundary between colluvium and residuum at 55 cm (Figure 3). This boundary is not visibly offset. The material above this boundary appears to correlate with the early Holocene stoneline and overlying colluvium in nearby trench ST–68 (Figures 4 and 5). The materials beneath this boundary exhibit characteristics primarily dependent upon past and present drainage conditions. For example, cobbles within the pseudopaleosol do not have oxidized weathering rinds as do those within the residuum and colluvium above it. Instead, the cobbles within the pseudopaleosol are etched, giving no evidence of ever having been part of the oxidized zones. A further complication of the picture involves possible Holocene degradation advancing irregularly across the surface of the pseudopaleosol. For example, the mottled, v–shaped area between 100 and 150 cm indicates a zone of seasonal water table fluctuation. Most likely, the pseudopaleosol no longer maintains quite as much perched water as it did during its earlier development.

In summary, then, the main fault feature in BHT–53 is not a simple result of colluvial deposition within a fissure produced by late Pleistocene displacement. Indeed, the colluvium/residuum boundary occurs at about the 55 cm depth—it is certainly not coincident with the soil–bedrock boundary as implied by both earlier interpretations. The large size of the pseudopaleosol, or soil tongue, developed within this fracture has contributed to cobble orientation and other unique, apparently non–tectonic features that we were unable to corroborate at numerous other exposures along the Maidu East fault zone. Of course, there always remains the possibility that small displacements could have occurred within the feature during the last 100,000 years without being recorded in strata of such irregular nature.

SUMMARY AND CONCLUSIONS

Fault features within the Mehrten Formation near the proposed Auburn dam exhibit two basic types of soil and clay formation. The first, under good drainage, produces reddish clays in which only halloysite and iron oxides dominate. The second, under poor drainage produces grayish clays in which both halloysite and montmorillonite dominate and iron compounds are reduced.

Good drainage is typical of most of the soils on the dominant Mehrten conglomerate and on the few sandstone outcrops such as occur along a remnant of a fault–line scarp in trench ST–68. The ages of these soils vary depending upon the degree of erosion suffered during the early Holocene pluvial period. The oldest surfaces occur on a nearly flat–lying drainage divide (trench BHT–70) and the youngest between the fault–line scarp and the main shear of the Maidu East fault zone (trench BHT–106).

Poorly drained soils are rare in the Mehrten Formation for they are only associated with faulting. A humic gley soil occurs in a spring area (trench BHT–66) where halloysitic colluvium of Holocene age overlies a montmorillonitic–halloysitic unit. The latter unit appears correlative with the Foothills paleosol and is of probable Wisconsin age because it contains spruce and hemlock pollen. The colluvium was derived from well–drained soils developed on the Mehrten Formation upslope. The iron oxides in it have been reduced, but montmorillonite has not yet formed. In nearby trench BHT–69, the montmorillonitic unit overlies part of a 60–cm offset in the Maidu East fault zone. Shrinkage cracks filled with iron oxide coatings within the unit may indicate that a slight lowering of water table has occurred since formation of the montmorillonite.

Fault features elsewhere within the Maidu East fault zone were interpreted with the above noted drainage considerations in mind. A probable sequence of events concerning the age of the Maidu East fault includes the following:

(1) Deposition of the Mehrten Formation in a river channel during the Miocene about nine million years ago (O'Brient, 1978, p. 11).

(2) Downcutting of the American River through Mesozoic bedrock during the Pleistocene beginning about two million years ago with accompanying soil formation on the now–abandoned river channel.

(3) Displacement and fracturing of the Mehrten Formation along the Maidu East fault zone.

(4) Translocation and formation of halloysitic clay and iron oxides within the relatively well–drained shears and fractures of the fault.

(5) Erosion and 30–meter recession of the fault scarp west of the main shear in trench BHT–53.

(6) Eventual plugging of shears within the fault zone leading to decreased permeability and perched water conditions.

(7) Montmorillonite and continued halloysite formation under reducing conditions within shears and fractures resulting in "soil tongues" and/or "pseudopaleosols." Pseudopaleosols occur beneath the normally oxidized zone of well–drained soils. They are irregular clayey bodies that may be mistaken for paleosols though they do not directly represent formerly stable land surfaces. Pseudopaleosols are forming contemporaneously although their principal development appears to have occurred prior to the Holocene.

(8) Extensive slope stripping and deposition of the Foothills colluvium during the early Holocene pluvial period (Borchardt, Rice, and Taylor, 1980).

(9) Partial re–oxidation of the upper surfaces of pseudopaleosols as a result of local slope stripping without subsequent deposition (trench BHT–106) or as a result of reduced precipitation during the Holocene (trench BHT–53).

In sum, major displacement along the Maidu East fault zone occurred after the beginning of the Pleistocene and before pseudopaleosol development during the late Pleistocene.

Despite some striking trench exposures that initially appeared to suggest displacements of surface soils, we found no unequivocal evidence for movements more recent than about 130,000 years ago along this fault zone. Detailed analyses (pH, particle size distribution, Ca/Fe ratios, and clay mineralogy) of three soil profiles on either side and above the main fault break in BHT–53 showed no clear offset. Interpretations favoring movement more recent that 100,000 years must consider (1) the irregular nature f pseudopaleosols, (2) the differing bedrock types and drainage onditions on either side and above the fault, (3) the expansive haracter of the pseudopaleosol which might have a tendency to estroy recent evidence for tectonic shearing, and (4) the col- uvium/residuum boundary that occurs at shallower depths than he soil–bedrock boundary. We found no conclusive evidence for ectonically generated slickensides within the pseudopaleosol al- hough slickensides of tectonic origin do occur in relatively un- eathered portions of the fault zone. Nevertheless, there is a light chance that small displacements along the Maidu East ault zone could have occurred during the last 100,000 years ithout being recorded in the strata available.

GLOSSARY

ANGULAR ORPHANS – Angular fragments separated from weathered, well–rounded cobbles in colluvium derived from conglomerate.

FAULT–LINE SCARP – A scarp which has been produced by differential erosion along an old fault line.

PSEUDOPALEOSOL – A pedogenic feature that may be mistaken for a paleosol (fossil soil).

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APPENDIX: METHODS

Particle Size Distribution

The particle size distribution of soil samples was determined with the hydrometer method (Day, 1965) by using sodium metasilicate instead of calgon. Carbonates were removed by treatment with pH 5 sodium acetate. This was followed by a mild hydrogen peroxide treatment as an additional aid to dispersion. An Iowa jet dispersion apparatus was used to further disperse the samples (Chu and Davidson, 1953). The temperature of suspensions was controlled at 25C with the use of a water bath and inexpensive temperature controller (Blue M Electric Company, Blue Island, Illinois).

X–ray Diffraction of Clay Fractions

Clay fractions (< 2 um) were obtained from the samples dispersed with sodium metasilicate. Approximately 0.7 g of sodium metasilicate was added to each 50 g of soil sample during the particle size analysis. This small amount of sodium metasilicate or its reaction products produced no detectable interference with x–ray diffraction analysis. Calgon (Na_3PO_4) was avoided as a dispersant because it reacts with the clay fraction to a greater degree than sodium metasilicate.

Magnesium saturated clay (< 2 um) samples were used to prepare slides by the smear–on–paste technique (Theisen and Harward, 1962). A 15 cm flexible plastic rule was used instead of a spatula for spreading the paste (Borchardt, 1977b). Slides were air dried one hour, placed in a 54 percent humidity chamber overnight, and x–rayed in a controlled 54 percent relative humidity environment. The absence of mica was shown by the absence of a 10A peak. Next, the sample was heated at 110C for two hours in glycerol vapor (Brown and Farrow, 1956) which was then allowed to condense onto the sample overnight. Another Mg saturated sample was heated at 60C for two hours in ethylene glycol vapor which was then allowed to condense overnight. X–ray patterns for ethylene glycol treated slides of montmorillonite and beidellite standards were identical, showing expansion to about 17A. "Beidellite" would have been identified by its resistance to expansion when solvated with glycerol vapor (Harward and Brindley, 1964).

Potassium saturated slides were similarly prepared and subsequently heated to 110C, 300C, and 550C. Vermiculite would have been indicated by collapse of 14A peaks to 10A after K saturation, drying at 110C, and x–raying at 0 percent humidity. Kaolin (Kaolinite or halloysite) was identified (in the absence of a 14A peak) by the disappearance of the 7A peak after heating a K–saturated sample for three hours at 550C. The presence of halloysite rather than well–crystallized kaolinite was indicated by the development of a 7A peak upon air drying of field moist samples. Chlorite would have been indicated by the presence of a 14A peak after 550C heating. Decreases in the size of the 7A peak with corresponding increases in the 14A peak due to 550C heating would have been an indication of chlorite, not kaolinite. Non–crystalline material was considered high in samples with small peaks or none at all.

pH

The pH was determined by mixing the soil with water until it was the consistency of a paste. A Chemtrix Type 60A pH meter was used for the determination.

Ca/Fe Ratios

Calcium and iron were determined by using a Phillips x–ray spectrometer and a method of sample preparation modified from Borchardt and Theisen (1971). Briefly, air–dried soil was sieved through a no. 40 sieve (420 um) and then added to a 32 mm aluminum Spex cap containing polyvinyl alcohol as a backing material. This was pressed in a die assembly at 2300 kg/cm^2 (also approximately 2300 tons per square foot) to form a smooth sample surface.

Ca was determined by measuring the count rate of the Ca_{K_α} peak at 113.10°2θ. The chromium x–ray tube was operated at 30 kv and 10 ma. X–rays were detected with a LiF crystal and flow–proportional counter operated in a less than 300 um vacuum at 1530 volts. A pulse height analyzer was used with the baseline at 4.0 volts, and the window at 11.0 volts.

Fe was determined by measuring the count rate of the Fe_{K_α} peak at 51.75°2θ. The chromium x–ray tube was operated at 45 kv and 25 ma. X–rays were detected with a LiF crystal and scintilation counter operated in air at 960 volts. A pulse height analyzer was used with the baseline at 4.0 volts and the window at 20 volts.

The count rates for both Ca and Fe were compared directly to those for a standard andesite (USGS–AGV–1) which contains 3.50 % Ca and 4.73% Fe according to Flanagan (1973, p. 1190). This comparison was made after every three samples to correct for instrumental instability. Background and matrix corrections were unnecessary because the background count rates were insignificant and the matrix was similar for all samples.

Color

Soil colors were determined by comparison to the standard Munsell soil color charts. When color names are given, the name refers to the first cited notation in parenthesis (Soil Survey Staff, 1951, p. 203). For example, brown (10YR5/3d, 2/2 m) refers to the dry color, brown (10YR5/3d), and the moist color, very dark brown (10YR2/2m). This notation for dry (d) and moist (m) colors is becoming more common in the literature (Buntley and others, 1977, p. 401) and avoids confusion in preparing field descriptions.